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SEPTEMBER 1981

Final Report

Document is available to the U.S. public through the
National Technical Information Service,
Springfield, Virginia 22161

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
Office of Research and Development
Washington, D.C. 20593

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FEASIBILITY STUDY FOR AN ADVANCED LIGHTED AID TO NAVIGATION

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16. Abstract

This report discusses a Coast Guard advanced aid to navigation network. Various light sources, positioning systems, and radio links are investigated for suitability to solar powered marine aids. A modular microprocessor-based aid, capable of self diagnostic monitoring and differential LORAN-C positioning, is described. A communication system between the aids and shore stations, using conventional or meteor burst VHF or a GOES satellite link, is examined, showing the first and last options to be most viable. Inter-aid flash synchronization schemes, and data transmission formats, polling methods, and system performance analysis are discussed. Having established the technical feasibility of the advanced aid concept, cost and reliability estimates are performed on the proposed systems. Finally, recommendations on areas requiring further study are presented.

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EXECUTIVE SUMMARY

The U.S. Coast Guard maintains a network of aids to navigation to assist in safe passage of maritime traffic in rivers, harbors, and harbor entrances throughout the United States. This network, comprised of some 15,000 fixed and moored (buoy) aids, supplies position information to mariners via visual markers and flashing lights. The Coast Guard is studying the use of solar photovoltaic arrays to individually supply energy to these aids in the coming years. Preliminary estimates showed that approximately 500 aids would require more power than the envisioned 70 watt panels could deliver. This is a problem for the Coast Guard because it could preclude powering all the aids from the same type of energy source.

The Applied Physics Laboratory of The Johns Hopkins University was asked to investigate various aspects associated with this problem, specifically including reduction of aid electrical power requirements and design of the overall advanced aid network. Early investigation indicated that significant power saving could be realized only with a more efficient light source. Based upon our studies, however, such a light source is not available at this time, and its development was beyond the scope of this report. Therefore, APL was directed to concentrate the majority of its efforts towards configuring an advanced aid concept which would reduce total life cycle costs for the network in the future. Any impact of these advanced features upon aid power consumption was also to be noted. The result is the "Advanced Lighted Aid to Navigation" concept.

As described in this report, the advanced aid network will be able to perform the same function as the present aid network, visually indicating channel boundaries, hazards, and navigational waypoints. It will also be able to synchronize the flash patterns of groups of aids to make them more visible and provide more useful visual information to the mariner. Each District Headquarters will be able to ascertain daily the operational status and position of each of its aids via a telemetry link. Diagnostic information will be available on malfunctioning aids to help determine the severity of the problem existing on the aids, and assign priorities to maintenance crews.

Deployment and repair activities (when needed) will be performed using a microprocessor-based diagnostic tester carried to the aid by the maintenance crew. Aid initialization, diagnostics, and checkout will be performed either by the tester itself or by the crew using prompts from the tester.

The typical advanced aid to navigation will consist of a light, battery, and support platform (buoy, structure on a piling, etc.) as do the present aids. In addition, it will have a radio transceiver, microprocessor-based controller, and Loran-C receiver (moored aids only). The power for the flashing light and electronics will be generated by a solar array and stored in the rechargeable battery. The reliability goal of the advanced aid is a 5 year meantime before failure.

After a study of the light sources presently available, it was concluded that the two most viable were the present incandescent lamp and a xenon flash tube. The incandescent bulb would be run at slightly less than its rated voltage to increase its expected lifetime. Xenon flash tubes look promising if run in a "flicker" mode, thus allowing the eye to focus on them. Further study is needed to evaluate power requirements and bring down the cost, however. Incandescent lamps are therefore still the best light source immediately available.

To overcome the need for replacing the batteries yearly, the aids will use secondary lead-acid 12-volt batteries, recharged with power supplied by a solar array (or alternate source in a few select locations). Power load projections indicate that 97% of the aids will require at most a 400 ampere hour battery with a 35-watt solar panel. Most of the remaining 3% could use a 70-watt panel and larger battery to meet their needs.

The battery charging will be through a ripple-shunt regulator under microprocessor control. Battery temperature, voltage, and capacity together with solar array output will be used as inputs for the charge control algorithm. These quantities will also be used in creating the daily diagnostic status word, indicating such things as burned out or depleted light source, low battery voltage or state-of-charge, zero solar array current, or power system short.

All moored aids (buoys) will have a Loran-C receiver for determining the position of the aid. Assisted by the microprocessor, the receiver will calculate time difference information from two or three secondary Loran-C signals. This information, sent to District Headquarters as part of the aid status message, will be used in conjunction with information from stationary monitors to determine the aid's position within 30 meters accuracy. Knowing where the aid should be, a computer will automatically flag any buoys off-station.

The communications link used to transmit information to and from the aids can be configured using any one of several options. The three studied most closely in this report are a conventional line-of-sight VHF system, a meteor burst VHF system and the GOES satellite system. Each option has its own advantages and drawbacks, but all appear viable for this application.

The conventional VHF system will use Coast Guard high-level antenna sites and transceivers to communicate with the aids. Monitoring the aids will require at most 15 minutes access to a VHF channel on each antenna site; many sites will require less or no time. This system is relatively inexpensive, reliable, and represents a low technical risk. It can tie in very well with command, control, and communication systems presently being looked at by the Coast Guard.

The GOES satellite system will use satellite and ground support equipment operated by the National Environmental Satellite Service (NESS, part of the Commerce Department). Monitoring the aids will require the full time use of one of the 266 transponder channels available on the satellite. This system provides the most reliable communications link with the aids and the simplest shore data distribution network. It is, however, more expensive than the other two systems, due partly to the low production quantities of GOES transceiver equipment presently being built. Indications are that producing a customized design in large quantities could make this option economically competitive with the VHF options, and further study in this area seems warranted.

A meteor burst VHF system will use six or seven shore transceiver sites to communicate with the aids throughout the country by bouncing its signals off appropriately located ionized meteor trails. The communications links are semi-random in nature, and last very briefly (less than a second or two). This system is fairly inexpensive and would be under the Coast Guard's direct control. However, the communications link is not as reliable as the other two options, and the technical risks associated with it are higher. While it appears that this system could be made to work, it does not appear as desirable as the conventional VHF or GOES systems.

Data distribution and processing requirements for the shore-based equipment are varied, but are not imposing. Most communication will take place via callup modems and phone lines. The standard terminal recently selected by the Coast Guard will be more than sufficient to handle any of the processing or control tasks.

In summary, the proposed system would benefit the Coast Guard in two areas: more reliable and flexible aid operations and more capabilities for flash synchronization and system integration.

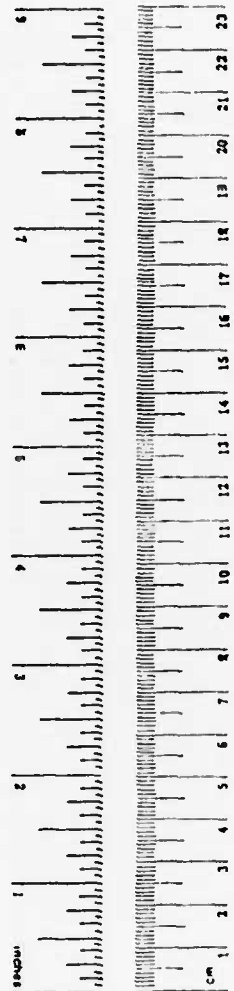
The body of this report discusses the major facets of the proposed Advanced Aid to Navigation Network. The five appendices are included to provide more systems details and design considerations.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

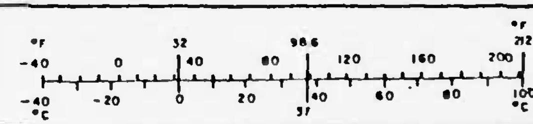
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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LIST OF ABBREVIATIONS

AAN	ADVANCED AID TO NAVIGATION
AANN	ADVANCED AID TO NAVIGATION NETWORK
ACK/NAK	ACKNOWLEDGE/NOT ACKNOWLEDGE
AN	AID TO NAVIGATION
ANP	AID TO NAVIGATION PLATFORM
BCH	BOSE-CHAUDHURI-HOCQUENGHEM
CDA	COMMAND AND DATA ACQUISITION
CDF	CENTRAL DISTRIBUTION FACILITY
CRC	CYCLIC REDUNDANCY CHECKS
C^2	COMMAND AND CONTROL
C^3	COMMAND, CONTROL, AND COMMUNICATIONS
DCS	DATA COLLECTION SYSTEM
EIRP	EFFECTIVE ISOTROPIC RADIATED POWER
EOT	END OF TRANSMISSION
FCC	FEDERAL COMMUNICATIONS COMMISSION
GOES	GEOSTATIONARY OPERATIONAL ENVIRONMENT SATELLITE
GPS	GLOBAL POSITIONING SYSTEM
ID	IDENTIFICATION
LRC	LONGITUDINAL REDUNDANCY CHECK
MCC	METEOR COMMUNICATIONS CONSULTANTS
MCS	MASTER CONTROL STATION
MTBF	MEANTIME BEFORE FAILURE
NBS	NATIONAL BUREAU OF STANDARDS
NESS	NATIONAL ENVIRONMENTAL SATELLITE SERVICE
NOAA	NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
PCM	PROCESS CONTROLLER MODULE
PILOT	PRECISION INTRACOASTAL LORAN TRANSLOCATOR

LIST OF ABBREVIATIONS (Concluded)

PPM	PARTS PER MILLION
RAM	RANDOM ACCESS MEMORY
ROM	READ ONLY MEMORY
TD	TIME DIFFERENCE
USART	UNIVERSAL SYNCHRONOUS ASYNCHRONOUS RECEIVER TRANSMITTER

INTRODUCTION

BACKGROUND AND OBJECTIVES

The U.S. Coast Guard maintains a network of aids to navigation to assist in safe passage of maritime traffic in rivers, harbors, and harbor entrances throughout the United States. This network, comprised of some 15,000 fixed and moored (buoy) aids, supplies position information to mariners via visual markers and flashing lights. The Coast Guard is studying the use of solar photovoltaic arrays to individually supply energy to these aids in the coming years. Preliminary estimates showed that approximately 500 aids would require more power than the planned 70 watt panels could deliver. This is a problem for the Coast Guard because it could preclude powering all the aids from the same type of energy source.

The Applied Physics Laboratory of The Johns Hopkins University was asked to investigate various aspects associated with this problem, specifically including reduction of aid electrical power requirements and design of the overall advanced aid network. Early investigation indicated that significant power saving could be realized only with a more efficient light source. Based upon our studies, however, such a light source is not available at this time, and its development was beyond the scope of this report. Therefore, APL was directed to concentrate the majority of its efforts towards configuring an advanced aid concept which would reduce total life cycle costs for the network in the future. Any impact of these advanced features upon aid power consumption was also to be noted.

At present, the Coast Guard visits each aid about every 12 months to replace burned out light bulbs, change batteries, verify flasher operation, and check its position. Special visits are also made to the aids when a report from a passing mariner indicates some malfunction has occurred.

These maintenance visits, whether made by a buoy tender or a land-based crew, are very costly to perform. It is also quite often the case that the visit was unnecessary; the aid either did not need normal servicing or an incorrect damage report was filed. As fuel prices and manpower costs continue to escalate, the present maintenance methods become less and less attractive.

On the more positive side, there have been a number of technological advancements in recent years that lend themselves to marine applications. Various individual programs

dealing with Loran-C navigation (PILOT), solar power generation and regulation, synthetic mooring materials, command, control and communications (C^3) systems, and more efficient and effective optical signals, have been undertaken by the Coast Guard. In an effort to utilize this work to the benefit of the aids to navigation network, the Coast Guard Office of Research and Development has undertaken the study of an "Advanced Lighted Aid to Navigation" concept.

The first phase of the investigation deals with the following areas:

1) Light sources and electronic flashing devices.

2) Battery and power systems.

3) Onboard aid diagnostics.

4) Station position monitoring.

5) Data link requirements between Coast Guard stations and navigational aids.

6) Cost estimates for instituting an Advanced Aid to Navigation Network (AANN).

Phases two and three will deal with developing a master plan for implementing the proposed Advanced Aid to Navigation Network (costs and schedule) and for the design, construction, and demonstration of an AAN prototype.

The scope of the effort leading to this report was to be quite broad. Where design tradeoffs are made, the advantages and disadvantages associated with each alternative are spelled out. The following is a list of design goals for the AANN:

1) The aids will operate autonomously for 5 years without any maintenance in a wide range of marine environments.

2) The aids will be of modular design for easy repair, standardization of parts, and system flexibility.

3) Deployment and servicing of the aids will require the same or lower technical skill as is presently used for aid maintenance.

4) The flashing lights on a group of aids can be synchronized to each other, producing a desired flash sequence.

5) The aid design will be suitable for either a fixed or a moored aid with little or no modification necessary. The aid should be usable wherever present aids are located.

6) The aids will be capable of self-monitoring their operation, such that when a need arises for servicing an aid, the appropriate Coast Guard Station will be made aware of the situation.

7) The proposed Advanced Aid to Navigation Network should be amenable with other Coast Guard C^3 systems.

Presently, the lighted visual signal system of Coast Guard minor aids to navigation consists, at most, of a light, flasher mechanism, battery, and support platform (buoy, structure on a piling, etc.) as shown in Figure 1. Based upon the list of design goals for the AANN, it is evident that a number of design changes will be required of the aids. The new aids may potentially incorporate equipment to generate and regulate power, determine positional fixes, and communicate with a Coast Guard station.

Because so many other functions will be added to the old aids, this report will refer to an advanced aid as an aid to navigation platform, or ANP as shown in Figure 2.

AIDS TO NAVIGATION DISTRIBUTION

The distribution and density of aids across the country are major factors in designing a new advanced aid network. There are presently about 15,000 aids located throughout the 12 Coast Guard districts. Approximately a fourth of these aids are buoys; the rest are fixed. Figure 3 shows the distribution of aids by Coast Guard district.

The new advanced system should be capable of incorporating 20,000 aids if necessary. It is assumed that no one area has more than 300 aids in any given 30 mile radius circle.

Those aids located in Alaska may present a problem because of the low solar insolation values and the low antenna angles to equatorial satellites found there. These northern aids may require nonstandard equipment for their communications and power functions to provide the same capabilities as the rest of the system.

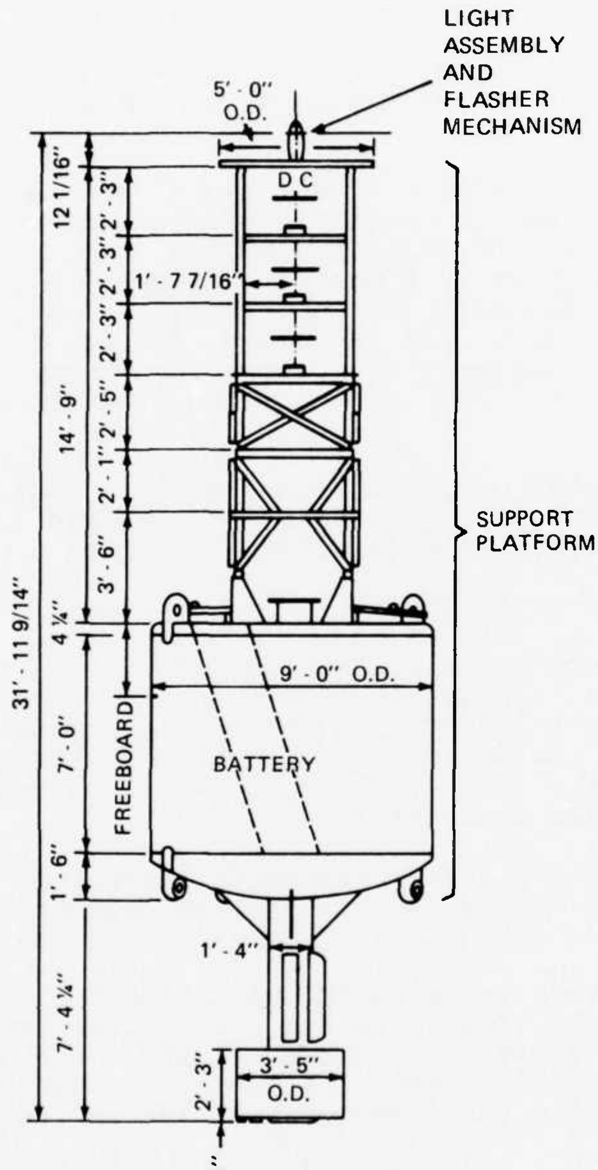

FIGURE 1. TYPICAL MOORED AID TO NAVIGATION.

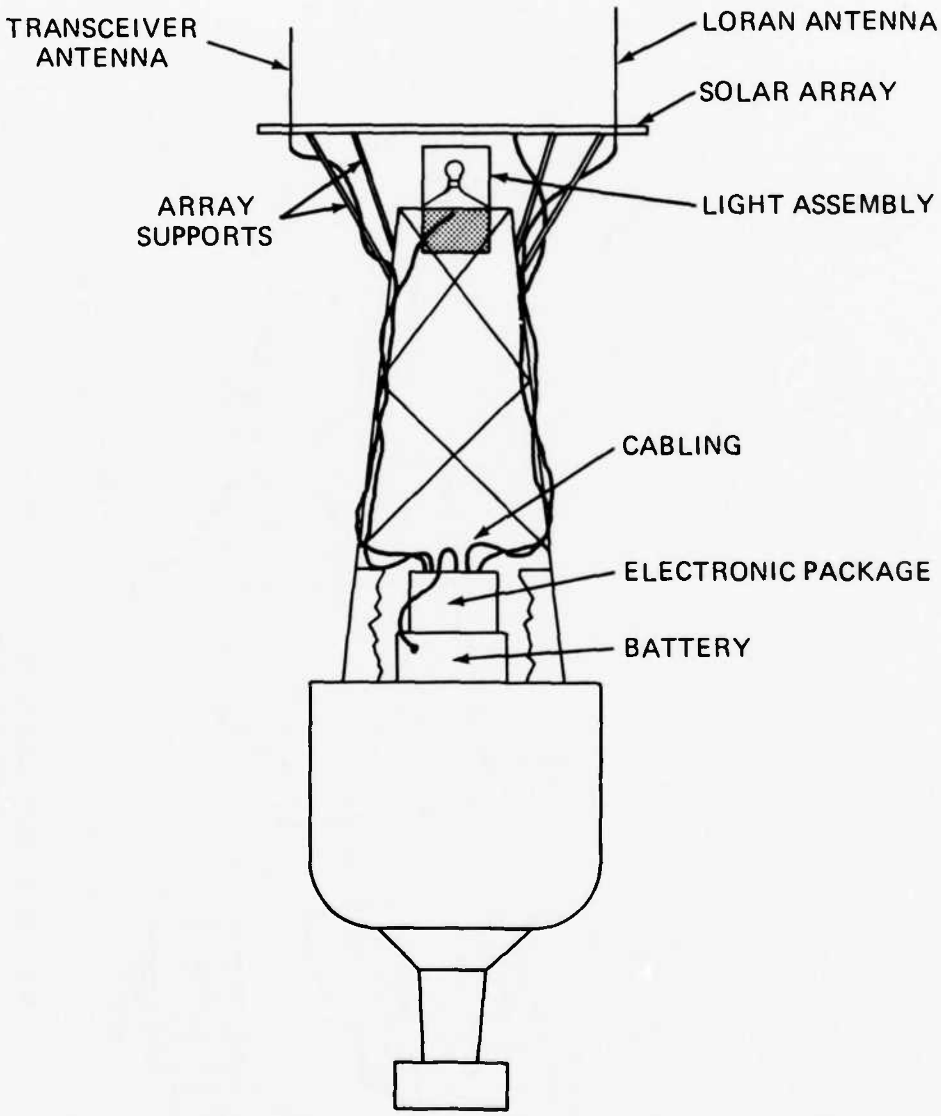

FIGURE 2 ADVANCED AID TO NAVIGATION PLATFORM (ANP).

U.S. Coast Guard Districts

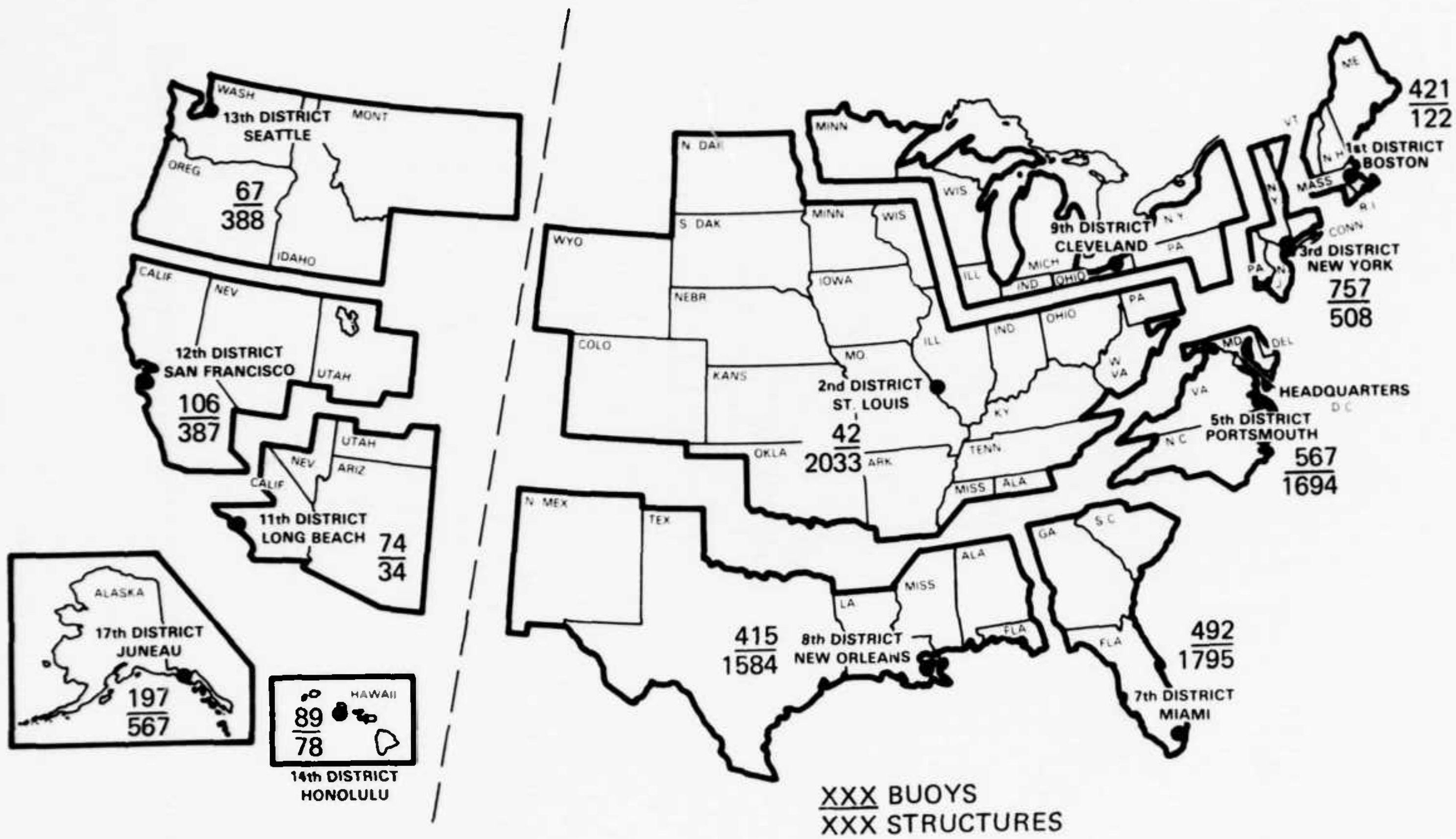

FIGURE 3 DISTRIBUTION OF AIDS TO NAVIGATION BY COAST GUARD DISTRICT.

ASSUMPTIONS

The following assumptions are made in this report:

1) Loran-C equipment will be used to determine buoy positions. This decision is based on DOT report No. CG-D-09-80* and the uncertain operational status of the Global Positioning System (GPS) in the 80's.

2) The Coast Guard, presently doing extensive research on natural energy sources and battery and solar array brand selection, will provide the appropriate battery and photovoltaic or energy source. APL will assess the capacity requirements for power generation and storage.

3) The Coast Guard is in a more appropriate position to assess costs associated with the procurement and maintenance of present aids to navigation. APL will provide its best estimate of cost as given by manufacturers for the proposed future system. The final cost determination will be made by the Coast Guard.

4) It is assumed that the ANP data are to be distributed to CG District Headquarters, where deployment and maintenance decisions will be made.

5) Flash synchronization requirements are 50 msec max between any two ANPs.**

6) The aids will operate in areas presently covered by the Coast Guard's line-of-sight VHF network.

7) The areas to be covered by the Advanced Aid Network are the continental United States, Alaska, and Hawaii. Warm weather ANPs will operate year-round, but some cold weather buoys will be removed in the winter.

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* Wolfson, J.A. et al, "Loran-Based Buoy Positions Auditing System - Analytical Evaluation," U. S. Coast Guard Research and Development Center, Report No. CG-D-09-80, February 1980.

** Personal communication with Lt. M. Milbach, Coast Guard Research and Development Center, Groton, Conn., 14 July 1981.

8) Nothing in the existing aid network is considered "sacred"; changes to any part of it are possible. Despite this degree of freedom, the study concentrates primarily on available system elements (solar arrays, batteries, transceivers, etc.) rather than advancing the state of the art in these fields. This emphasis is necessary due to the limited time available for this study.

9) Design features reducing the likelihood of theft or vandalism to the aid network will be the Coast Guard's responsibility.

LIGHT SOURCE

Many of the aids to navigation employ a flashing light to make them more visible at night. This light is useful in two ways; first as a warning merely that an obstruction, channel marker, or coast is nearby, and second, to convey information helpful in establishing how far away this object is from the viewer. The optical signal must be chosen so that it can be differentiated from other harbor lights, natural and man-made. A combination of signal colors, flash patterns, and intensities is used to convey the necessary information to the mariner.

The Coast Guard presently uses 12-volt incandescent tungsten filament lamps to provide the necessary light on their aids. The lamps range in sizes corresponding to currents of .25 A to 3.05 A. Flashing action and daylight disabling are controlled by an electronic flasher, producing flash duty cycles of 10%-75%, depending on the model flasher used. Lenses and filters are used to focus and color the light beam around the 360^{o} horizontal plane. As Table 1 shows, the distribution of flash patterns concentrates around the smaller lamps and lower duty cycles.

Although the intensity and duty cycles are selected with nearby aids in mind, there is no flash synchronization amongst aids. In preliminary studies conducted by the Coast Guard, it was shown that flash synchronization in a group of aids to navigation, especially near turns or harbor entrances, can greatly increase the effectiveness of the optical information. Achieving such synchronization, hopefully at lower cost, and with more efficient and reliable light sources, is one of the design goals of the AAN program.

The task described above can be broken into two parts; the light source itself and the flasher mechanism. The light source effort will be discussed first.

A number of light sources were surveyed at APL, including the present tungsten filament lamp, fluorescent tube lamps, xenon flashtube lamps, light emitting diode arrays (LEDs), and high pressure arc lamps. Because of the limited nature of this study APL has not attempted to design, build, or test any new or modified light sources. It was the intention, rather, to identify those existing sources that appear most viable and to highlight those deserving further study.

Of the light sources listed above, the tungsten filament, fluorescent tube, and xenon flashtube lamps look the most promising. The other sources were ruled out due to poor electrical efficiency, spectral output, short lifetime, or inability to flash quickly. Table 2 summarizes the advantages and disadvantages of all the light sources. For details on all the choices, see Appendix A.

TABLE 1 - USCG DISTRIBUTION TABLE OF EFFECTIVE LAMP CURRENTS

FOR VARIOUS LAMP SIZE - DUTY CYCLE COMBINATIONS*

Lamp Size (Amperes)	Duty Cycle (%) 10	12	16	18	30	33	50	75	Total % of Aids
I_{L_E}	.271	.278	.271	.278	.278	.258	.252	.252	
.25 %	6.10	.33	5.2	.07	1.10	.59	.38	.01	= 13.78
I_{L_E}	.621	.639	.621	.639	.639	.578	.559	.559	
.55 %	37.80	6.80	1.9	.70	7.03	.04	2.20	.04	= 56.51
I_{L_E}	.894	.916	.894	.916	.916	.816	.785	.785	
.77 %	11.48	2.7	.09	.43	2.18		.56	.06	= 17.50
I_{L_E}	1.38	1.42	1.38	1.42	1.42	1.24	1.18	1.18	
1.15 %	6.3	1.22	.08	.31	1.73		.518		= 10.16
I_{L_E}	2.62	2.76	2.62	2.76	2.76	2.23	2.10	2.10	
2.03 %	1.16	.18	.02	.05	.13		.13		= 1.67
I_{L_E}	-	4.15	4.15	-	-	3.42	3.17	3.17	
3.05 %	.29								= .29
TOTAL %	63.13	11.23	7.29	1.56	12.17	.63	3.79	.11	99.91

I_{L_E} = effective lamp current corrected for cold filament surge current.

% = percentage of aids in this category based on NOV 1979 SANDS Run showing 14082 Minor Aids to Nav

*Produced by U.S. Coast Guard Office of Engineers.

TABLE 2 - COMPARISON OF LIGHT SOURCES

	Tungsten Filament Incandescent Lamp	Fluorescent Lamp	Xenon Flashtube	High Density Discharge Lamp	LED
Approximate Efficiency	16 lumen/watt	80 lumen/watt	.75 lumen/watt[1]	50-200 lumen/watt	.04 lumen/watt
Spectral Distribution	Good	Good	Poor in Red	Poor in Red	Monochromatic--several colors to choose from
Flash Characteristics	Good	Poor-drastically reduces lamp life-time.	Only very short bursts (up to 20 milliseconds)	Very poor--requires warm-up time	Very good
Temperature range Characteristics	Good	Poor-loses efficiency in cold weather	Good	Good	Good
Lifetime	4-6 months (2-3 years/6 lamp assembly)[3]	Thousands of hours continuous burning.	7 - 10 years	Thousands of hours continuous burning	Many thousands of hours
Special Circuitry	None	Starter Circuit	High Voltage & Trigger Circuits	High Voltage & Starter Circuits	None
Price	$ 100[4]	$20	$1,000[2]	-	-
Comment	Still most attractive	Great efficiency --has some potential	Needs further study	Not practical	Not practical

Notes:
1. Based on flicker rate of 60 cps. This figure is a rough calculation; area requires further study.
2. Price could be brought down if produced in quantity.
3. Only lifetime based on actual Coast Guard aid experience.
4. Includes 6 lamps and lamp changer.

A fluorescent tube produces light more efficiently than the tungsten or xenon sources, but its efficiency drops quite a lot in cold weather, and the tube's normally long lifetime (thousands of hours) drops drastically when the tube is operated in a flashing mode. A mechanical shutter system could produce the necessary flashing pattern while operating the light continuously, but its use would entail additional servicing cost. Despite the above problems, the fluorescent tube is still promising enough to deserve further attention.

A xenon flashtube produces a very short, intense burst of light when an arc briefly forms between two electrodes in a xenon gas atmosphere. The flashtube is ideally suited to applications requiring high flash rates--pulses can be as short as 1 micro-second or as long as 20 milliseconds. The pulses of light are produced very efficiently, with visible radiation approximately equivalent to 6000° Kelvin.

Unfortunately, these light bursts are usually so intense that, although short, saturation of the eye prevents an accurate estimate of light source size and relative placement. This can make relative distance estimations completely inaccurate. "Flickering" the flashtube rapidly and at low output levels can overcome this problem by approximating a continuous light, but much of the xenon tube's efficiency is lost. Coating the flashtube with a photo-phosphorescent material may also help smooth the pulse shaping.

Another problem with the xenon tube is that it requires high voltages to operate. These voltages are produced by a "step-up" transformer and energy storage circuit. A xenon light source assembly is estimated to cost about $1000 each in production quantities. Assuming further efforts can bring this cost down, the use of a xenon flashtube operated in the "flicker" mode still looks promising, and requires further experimentation.

The tungsten filament incandescent lamp has a number of attractive characteristics. It has a relatively good spectral distribution and is a moderate power consumer, producing light with an efficiency of about 16 lumens/watt. The lamp can be easily flashed for varying periods, works well over a large temperature range, and requires no special drive circuitry. It also is very inexpensive ($3 each) and commercially available.

The major problem with tungsten filament incandescent lamps is their poor lifetime. Coast Guard figures show these lamps last an average of 4-6 months on an aid (lamp failure causes range from normal burnout to vibration and shock). Even with a six-bulb lamp changer (mechanically rotates good bulbs into flash position), the light source will have an expected lifetime of only 2-3 years. This is not good enough.

The lifetime of an incandescent lamp is exponentially related to its filament voltage - the higher the voltage, the sooner it will burn out. However, reducing the filament voltage 6% on a continuously burning lamp, for example, will about double the lamp's lifetime and reduce its light output by 17%. Further voltage reductions yield even more impressive gains in lifetime and higher losses in light output.

The key phrases in this approach are "reducing voltage" and "continuous burning." Unless the whole system voltage is dropped or the bulb is designed to operate at voltages greater than 12 volts, there will be some efficiency lost in generating a given amount of light. One could, for instance, replace an 0.55 A lamp with an 0.77 A lamp, and reduce the filament voltage to 10.3 volts. These changes would increase lamp lifetime six-fold, produce the same light output as did the smaller lamp, and use about 40% more current.

The above calculations are based on a continuously burning lamp, not a flashing one. We have been unable to determine, either from the Coast Guard or the manufacturers, what relationship exists between flash rate and lamp lifetime. This relationship, and the whole area of incandescent bulb failure modes, should be investigated further by the Coast Guard.

Despite its inefficiency, the tungsten filament incandescent bulb is still the best light source presently available for use on the aids to navigation. Further investigation of incandescent, xenon flashtube, and fluorescent lamps is, however, recommended.

Flash synchronization will be accomplished by using a microcomputer controller on each aid to navigation (see later sections for more details). The controller will be able to produce any desired individual flash pattern under software control, and will synchronize this pattern with those of any number of neighboring aids to within 50 msec. Synchronized flashing may be achieved between any aids as long as they all use the same RF link (VHF transmitter, etc. - see the communications link section). This requirement should be no problem, since in almost all cases, neighboring aids will be on the same link. The controller will be used to enable the flasher at night and detect when a lamp has burned out.

POWER SYSTEM

Most lighted minor aids for navigation presently use a primary air-zinc battery to supply power to the lamp and flasher mechanism. Because these 1000 Ah batteries are not rechargeable, they must be replaced about once every two years with fresh batteries. The old batteries are transported to special sites for disposal because they contain environmentally hazardous materials, such as mercury.

In an effort to cut down the procurement, maintenance, and disposal costs for the aid to navigation power systems, the Coast Guard undertook research into alternate energy sources and storage systems. After investigating such sources as thermal, wind, and fuel cells, it was decided that solar photovoltaic arrays provide the best source of electrical energy for most marine aid to navigation applications. Similar research into storage systems concluded in the selection of a lead-acid secondary battery.* These batteries will have a 100 Ah capacity, and can be used in parallel to provide greater storage capability.

Because the Coast Guard has done extensive testing on various makes and types of solar arrays and batteries, that work will not be repeated here. This study instead concentrates more on how best to utilize these components within the constraints of the AAN system.

Many considerations are involved when sizing a solar array and battery. The power load, maximum surge currents, load distribution, predicted degradation due to aging, location of the aid, orientation of the solar array, and relative costs of equipment must all be looked at before an optimized system can be selected. Permanent damage can occur to the battery when it is discharged below 50% capacity in below freezing temperatures, and there will be some periods of time when little or no useful solar energy will be available for days. Appendix B discusses many of these factors in greater detail.

Using data such as described above, a computer program could be adapted from currently existing programs to select the proper size array and battery for any given aid. Preliminary analysis shows, for instance, that a horizontally-mounted 70 watt solar panel located at 40°N latitude, could support a 10 Ah daily load year round with a 500 Ah battery. These figures already incorporate a poor weather reserve, with the battery never falling below 50% depth of discharge.

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*Allen, W.E., "Evaluation of Solar Photovaltaic Energy Storage for Aids to Navigation," U.S. Coast Guard Research and Development Center, Report No. CG-D-5-81, November 1980.

The ANP power system will employ a regulator to control the charging of the battery and prevent gassing due to overcharging. The charge regulator will be microprocessor based, employing a linear shunt as the control element. Charge regulation decisions will be made using information such as battery voltage, temperature, state of charge, and available solar array current. Experimental data show this kind of regulator should yield maintenance-free battery operation of 5-6 years.*

*Allen, W.E., "Design and System Level Performance of a Battery Charge Regulator for Solar Photovoltaic Powered Aids to Navigation," JHU/APL CP-083, August 19, 1981.

MICRO CONTROLLER

The process controller module (PCM) is the heart of the ANP electronics package, and directs the actions of all the other pieces of equipment on the platform (Figures 4 and 5). The controller is comprised of a 4-bit CMOS microprocessor-based microcomputer, clock, analog to digital converters, and flasher, power regulation, and control circuitry (Figure 6). For a more detailed description of the PCM design, see Appendix C.

The operation of the PCM will vary little from day to day (Figure 7). For much of the day, the ANP is in a low-power standby mode, with only the PCM receiving power. This mode is interrupted to perform three types of activity: flashing the light, determining ANP status, and communicating with the master control station. A typical 24-hour operation cycle would be as follows:

As night approaches, the light falling on the solar array, as sensed by the array current, drops below some predefined level. The microcomputer, under software control, will access the information stored in RAM to determine the proper flash sequence. This sequence will be gated with the internal crystal clock to synchronize it to the rest of the ANP chain. At the proper times, an output signal to the light source will be toggled to create a flash pattern. The light source current will be sensed to assure proper flash action.

The light will continue flashing until just after dawn, when the increasing light level will again be detected by the solar array current. The microcomputer will stop sending flash pulses, and the light source current will be checked to insure the light is off. The ANP returns to the standby mode.

At some predefined time (stored in RAM) during the day, all ANPs enter the diagnostic mode. Various measurements, such as battery voltage and array current, will be made. The data will be processed by various algorithms to make a determination of ANP operational health. A status word will be created for later transmission to the MCS.

The Loran-C receiver (Appendix D) will now be turned on and given time to lock-up. In an effort to stabilize oscillator performance quickly, small crystal temperature-control modules will be enabled in the Loran receiver at the start of the diagnostic mode. If the receiver has trouble locking up, it will be assisted by various algorithms stored in the microcomputer. Upon lockup, TD data will be read into the PCM and stored for later transmission. The ANP now reenters the standby mode.

The ANP will enter the communications mode at another predetermined time. This phase of the ANP operation will vary somewhat depending on which communications link is chosen. In general,

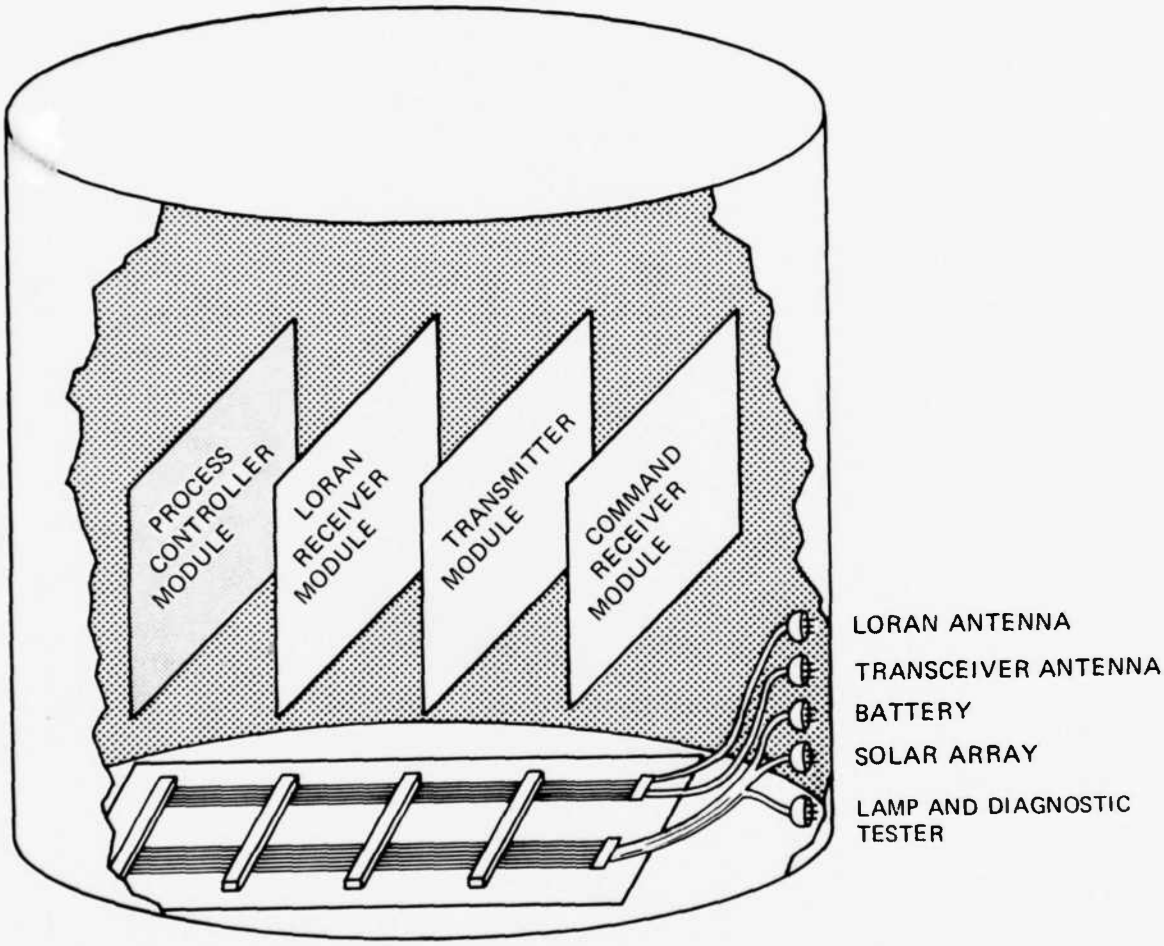

FIGURE 4 ANP ELECTRONICS MODULES.

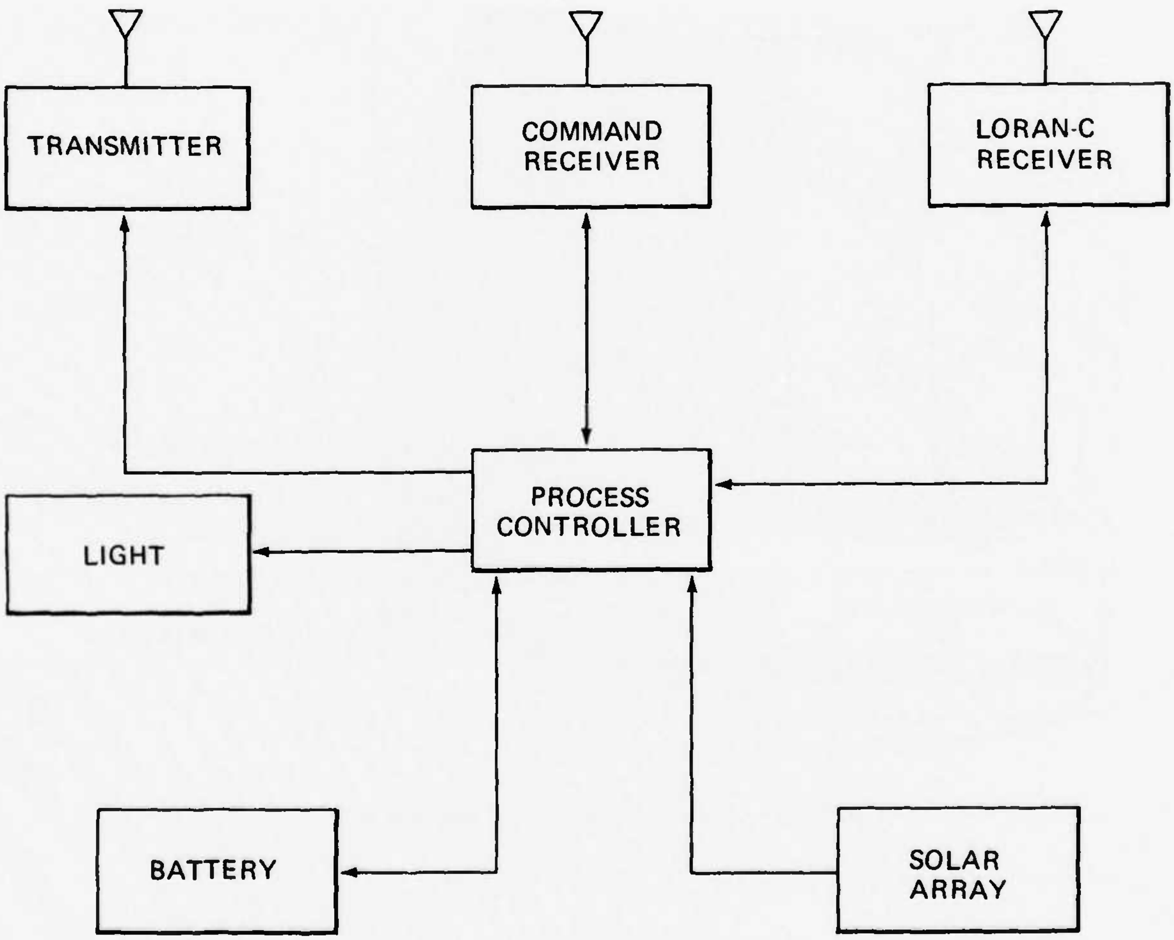

FIGURE 5 ANP BLOCK DIAGRAM.

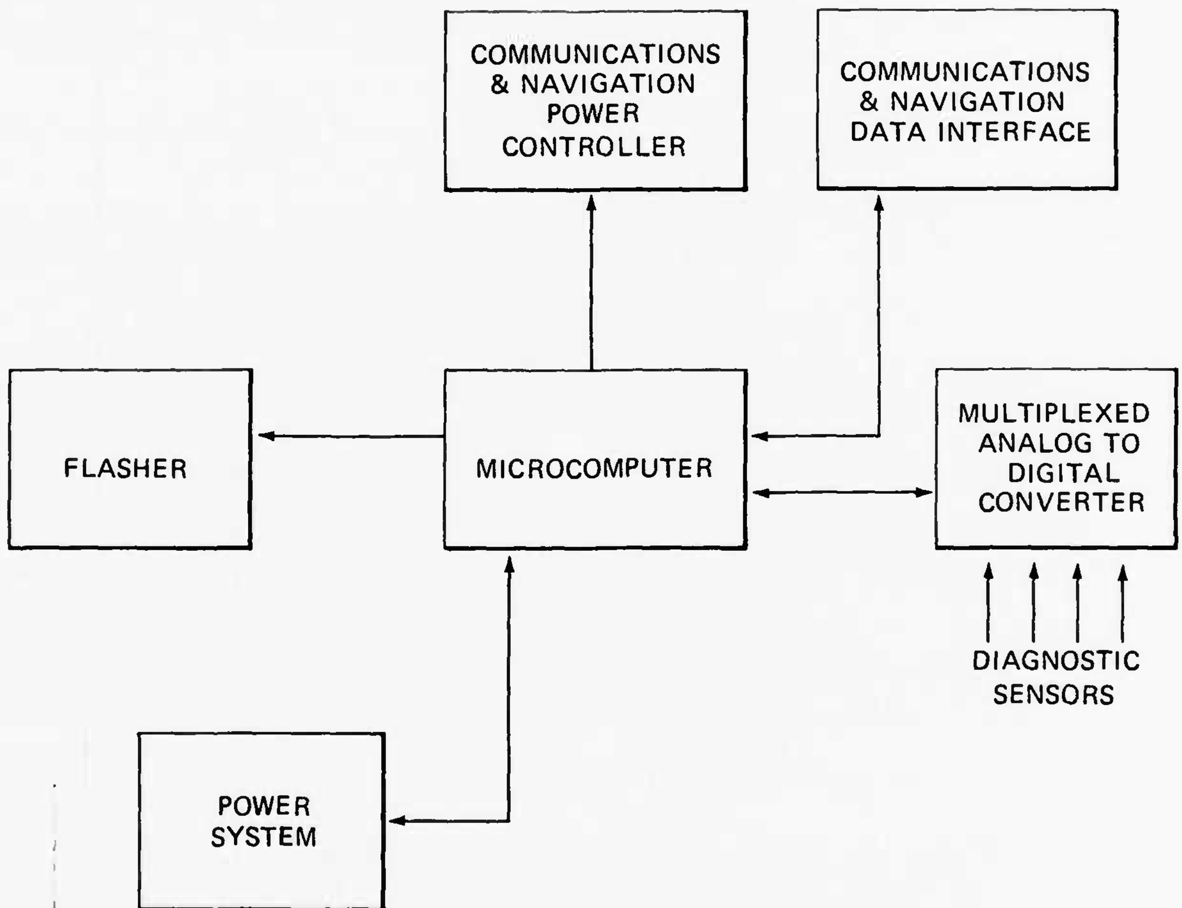

FIGURE 6 PROCESS CONTROLLER MODULE BLOCK DIAGRAM.

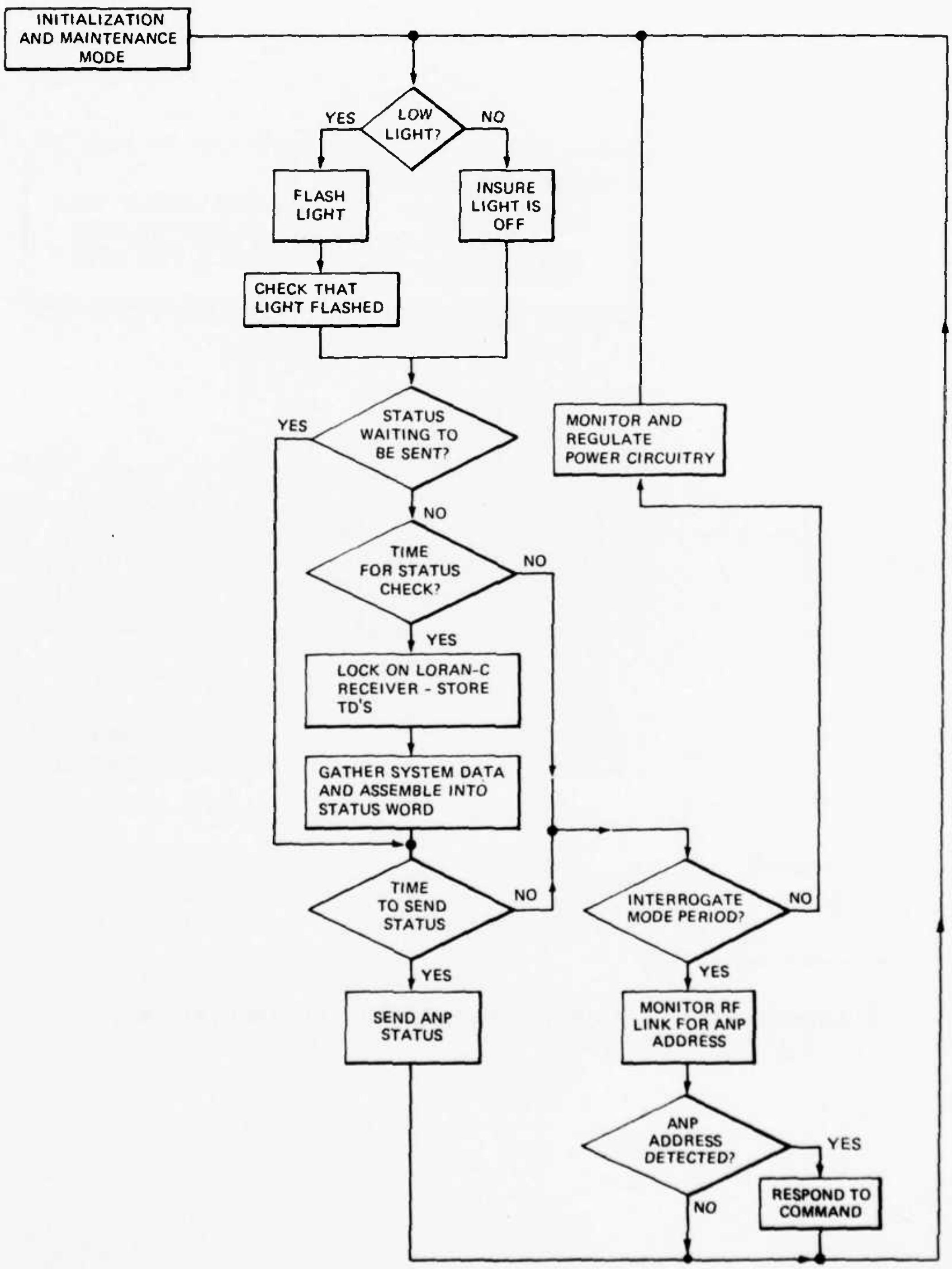

FIGURE 7 DAILY ANP FLOW DIAGRAM.

however, the microcomputer will format the diagnostic information it has stored in RAM, and add error-detection bits and ID number. By enabling the transmitter and receiver at appropriate times, the diagnostic status will be sent to the master control station via a radio link. In return, the MCS will transmit a clock synchronization signal to the ANP. The internal clock buffers will be adjusted appropriately by the microcomputer. The ANP once again reenters the standby mode, awaiting the start of the flash mode once again.

All the ANPs in a given area will enter the flash and diagnostics modes at approximately the same time. However, they will enter the communications mode in a staggered manner so that radio interference can be kept to a minimum. A more detailed description on the communications mode and the RF link is given in a later section.

COMMUNICATIONS LINK

One of the most important features of the Advanced Aid to Navigation Network concept is the ability of the Coast Guard to remotely monitor the functioning and position of their aids. To accomplish this task, some means of communication must be established between the aids and the CG groups servicing them. The next section briefly discusses what information needs to be passed to and from the ANPs. Following that section we will examine the suitability of various communications links to handle this information.

REQUIREMENTS

The first question to ask is why a communications system is required at all. Conceivably, buoys could be designed having such a high degree of autonomy and reliability that the cost of visiting them infrequently might be less than the communication system cost. Unfortunately, overall buoy "reliability" is also determined by collisions, drifting of buoys off-station, and other external events essentially beyond the control of the designer. Another consideration is the significant number of buoys erroneously reported out-of-order or off-station. Each of these erroneous reports must be checked out by the Coast Guard. Because of these "external" factors, the required visitation rate would still be too high even if the internal buoy subsystem reliabilities approached 100%. This implies a need for at least one-way communication from buoy to shore station which can indicate with a high degree of confidence that the buoy is on-station and operating properly. A status report received once per day from each buoy would probably suffice, although it might be desirable to have faster access to the small subset of buoys currently reported to be out-of-order. A worst-case longest diagnostic message, not including spares and overhead, is estimated to contain only 116 bits; 3 TDs @ 36 bits/TD + 8 status bits.

. The Coast Guard has also indicated a desire to synchronize the flashing lights of arrays of buoys to produce visual patterns such as a rippling "airport runway light" effect. This feature may be desired on many of the buoys used in channels, potentially representing about 70% of the total. This requirement implies either an extremely stable, expensive oscillator or two-way communication at least among the buoys themselves. Once we admit to adding a receiver for either timing or synchronization from nearby buoys, it may cost very little more to receive transmissions from the shore or from satellites. So it appears the need for two-way communication may be driven by the rippling light requirement, but this second link can also be useful in managing the large number of status transmissions.

The required coverage area is taken to be the entire continental U. S. plus offshore waters out to about 25 miles (i.e., out to RF line-of-sight). Coverage of Hawaii and at least the lower half of Alaska is also desirable. Fixed ANPs can utilize a directional antenna to increase the system gain. Because buoys may encounter pitch and roll angles of 30-40° or more, they will require an antenna providing essentially hemispherical coverage (gain of 0 dB or less).

LINK CANDIDATES

Given the need for a communications link, there are a number of propagation media that one can consider. The use of optical or sonic signals to communicate in this application appeared impractical; the propagation path would either be non-existent, too lossy, or filled with sources of interference. A more practical approach is to use a modulated RF link.

Several bands in the radio frequency spectrum have been considered. As a general rule, the cost and complexity of communications equipment increase with frequency. These factors, along with the limited-gain nature of the ANP equipment, favored a link in the HF to UHF frequency range ≈ 5 MHz - 700 MHz.

An HF transmission is capable of either reflecting off the E & F layers of the ionosphere (skywave) or traveling along the ground (surface wave). Both modes have problems; daily ionospheric changes make the propagation path erratic or lossy, or there is severe attenuation over land. The size, cost, and power required to overcome these problems were prohibitive for the AAN application. The HF band was therefore removed from further consideration.

Moving up in frequency, we encounter the VHF band, starting at about 30 MHz. Because the ionospheric layers no longer reflect the radio signal back to earth, VHF transmissions are conventionally limited to line-of-sight distances, roughly 25-100 miles, depending on the frequency, terrain, antenna height, and radiated power. An exception to this rule involves using ionized trails from meteors entering the atmosphere to reflect or reradiate the VHF signal back to earth. This somewhat unconventional technique, called meteor burst communications, can result in VHF links up to 1200 miles in distance.

Another possible link is to use a satellite to communicate with the aid to navigation platforms. This approach has the advantage of requiring only one Coast Guard base station to handle the control and data gathering tasks of the system. The satellite and the conventional and meteor burst VHF communications links will be discussed in more detail below.

VHF

VHF is limited basically to line-of-sight communication. To use this kind of a system for communicating to the ANPs would require a number of antenna sites located strategically along the whole U.S. coast and river channels to provide line-of-sight from any given aid to at least one antenna (Figure 8).

Each antenna site would have a VHF transceiver capable of transmitting approximately a 50 watt signal. Once per day the transceiver would individually poll the ANPs within its area of coverage to determine their status, and send the information collected to the District Headquarters for processing and distribution. The intelligence required to handle the polling sequences, timing, and district reporting would be provided by a small microcomputer located in Group Headquarters, via phone lines (Figures 9 and 10).

The U. S. Coast Guard presently operates a VHF communications system in the frequency range of 155-168 MHz.* The system is designed to receive a signal originating from, at minimum, a 1 watt transmitter up to 20 miles from the U. S. coastline. Coverage is also provided along major navigable rivers in the country's interior.

Because almost all ANPs would be located in an area with present Coast Guard VHF coverage, piggy-backing on this system would seem the logical first choice for a VHF link. Much of the existing receiving, transmitting, and antenna gear could be used for part of the day to communicate with the ANPs. Because of the short distances involved, the ANP would require only about a 5 watt transmitter.

A few problems exist with this approach. The communications equipment is presently controlled manually by an operator located somewhere in a Coast Guard Group. Access to a specific frequency is requested of the operator by a nearby Coast Guard station, and granted if that frequency is available. This method of gaining access to one of the six available frequency channels at an antenna site is far from standardized.

Allowing access to the present VHF transceivers by a microcomputer would require replacing the existing manually-controlled system with an automated one. This function could easily be incorporated into the microcomputer's programming, and would allow for more efficient use of the available communications equipment. It would also be possible to allow for passing messages among the various Coast Guard groups using that antenna chain. This equipment would collectively be known as a Master Controller Station (MCS).

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*Kissick, W.H., "Coverages of the MF and VHF Maritime Distress Communication Systems," U.S. National Telecommunications and Information Administration, Report No. NTIA 80-52, October 1980.

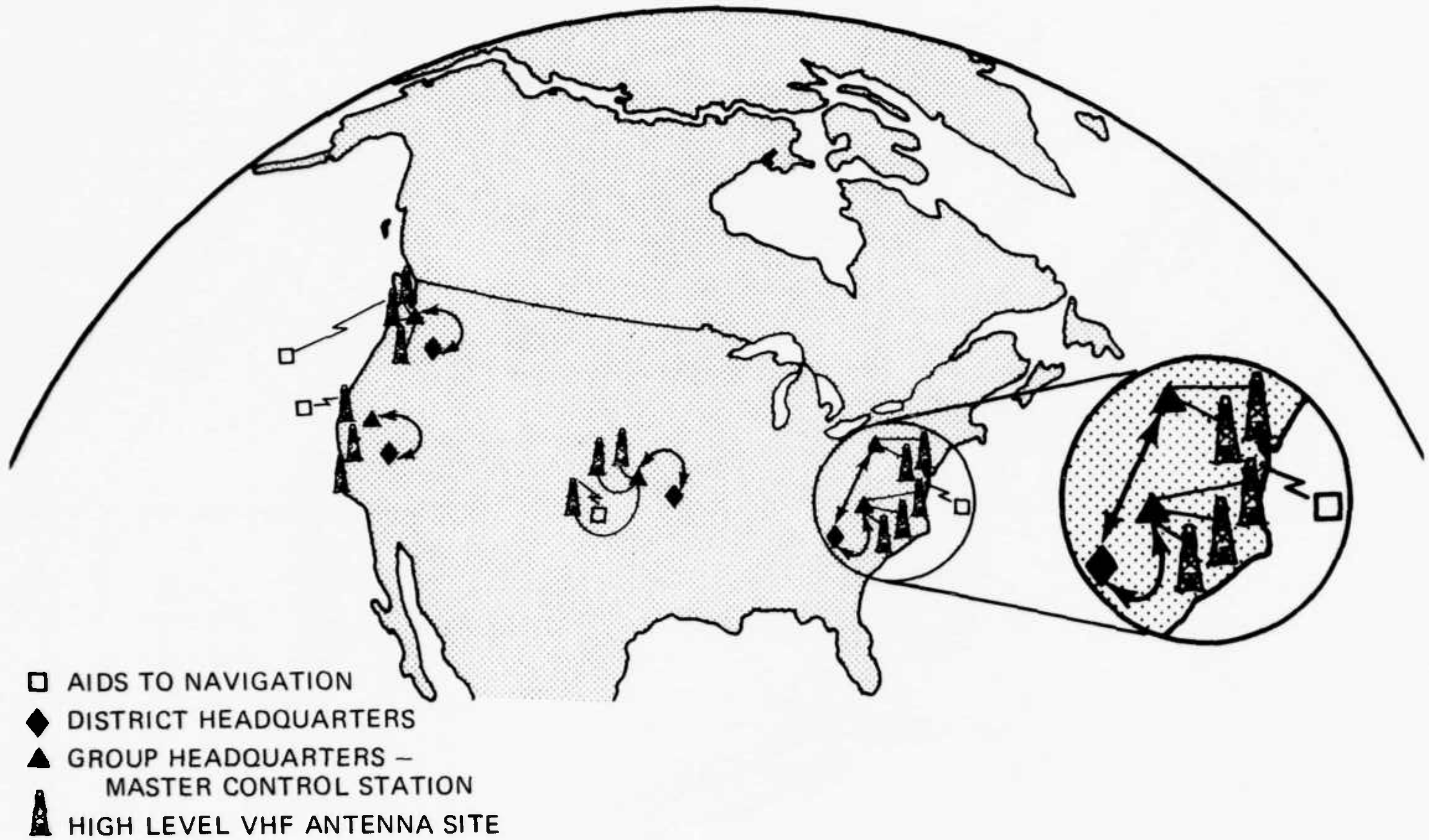


FIGURE 8 MASTER CONTROL STATION AND DATA DISTRIBUTION FOR VHF.

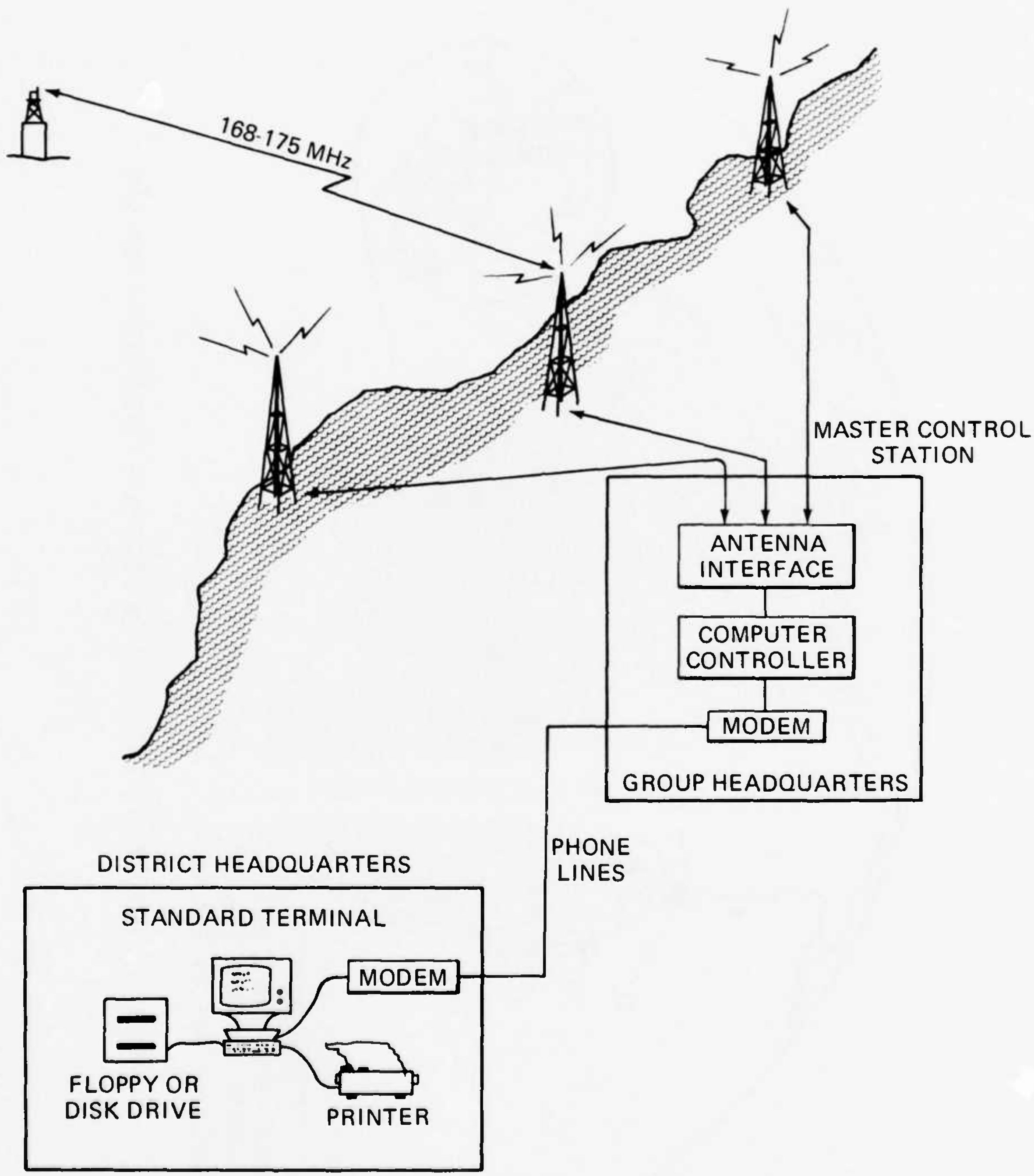


FIGURE 9 VHF MONITOR SYSTEM.

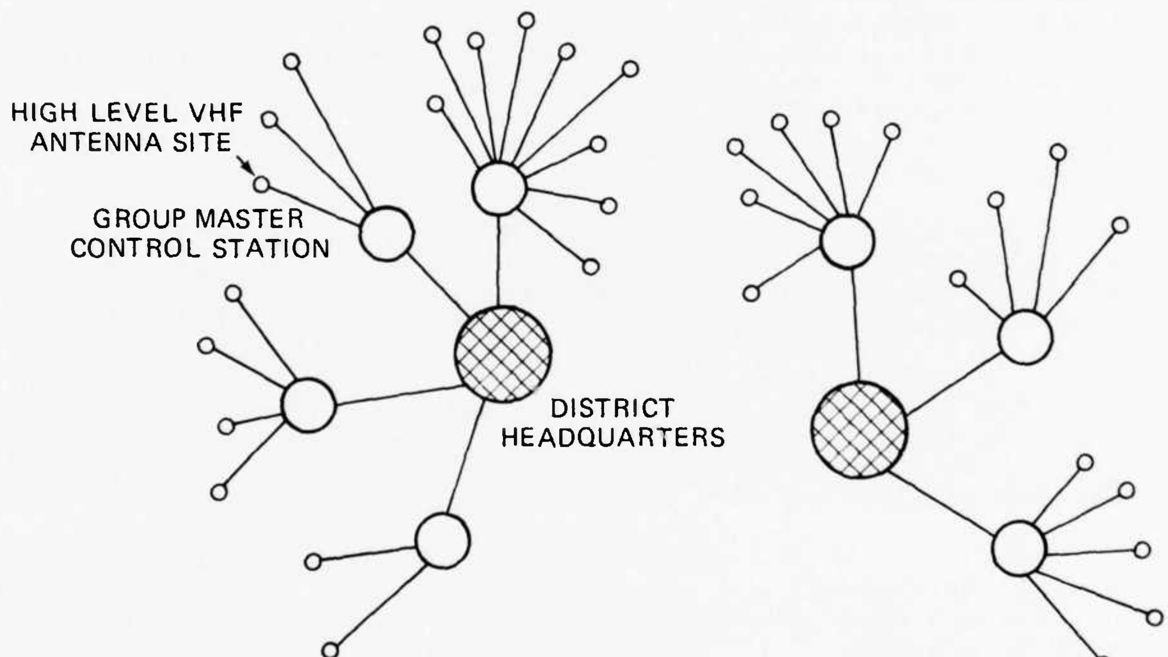


FIGURE 10 VHF DATA DISTRIBUTION.

After entering the aid monitor mode and gaining access to the appropriate communications channel, MCS would begin polling each ANP to determine its status. Part of this polling message would be a timing message for synchronizing the aids clock. The clock at the MCS generating this information need not be very accurate; as long as its short term drift component is low, all the aids in the area will be synchronized with each other. Synchronization between various MCS clocks in different groups is not required.

Assuming a bit rate of approximately 150 baud, it would take about 2 seconds to communicate with any given ANP (400 millisecond polling message, 800 millisecond status reponse, 400 millisecond separation space on each end). This is a rough approximation; the message formats and transmission rates could be changed. Given that no antenna site would be responsible for more than 300 ANPs, polling should require only 10 minutes transceiver time. Allowing for repolling those ANPs not reporting successfully the first time, the whole operation should at most require 15 minutes access daily to any given antenna site.

Once per day the microcomputer would transmit the collected status information to a computer in the District Headquarters via an automatic callup modem. The information would be processed, operational status would be determined for each ANP in the district, and corrective action would be initiated where necessary.

The possibility exists that a malfunctioning ANP would not turn off its transmitter, effectively disabling that VHF channel for use until the aid was serviced. For this or other reasons, the ANP transmitter will have a time-out feature.

It may be deemed desirable to allocate some new or existing channel exclusively for the AAN Network. Any number of command and control functions could be added to this communications network if desired.

The Advanced Aid to Navigation Network described above, with microcomputers controlling access to antenna sites and frequency channels, passing data and messages between group stations and District Headquarters, and processing and distributing information would obviously tie in with other Coast Guard needs. This command and control system, designed for aids to navigation, closely resembles the preliminary Coast Guard C^2 Project 9221.50 progressing in the test bed at Hampton Roads Group, Portsmouth, Virginia. That system, still in development, is designed to interface with District Headquarters, groups, subgroups, and individual ships together, thus automating various navigational, communications, "mail," and control tasks. Although it is not now explicitly designed for the task, the system could easily be configured to include the ANP monitoring in its operations.

The VHF link, therefore, appears to be a viable option for the communications required. It can be justified on its own merit, but looks even more advantageous as a part of a larger command and control network.

Meteor Burst

A meteor burst communication system is another type of VHF system, this one working in the low VHF band (40-100 MHz). It relies on the scattering produced by ionized meteor trails in the 80 to 120 km region of the ionosphere for propagating its radio signals. These trails reflect or reradiate the RF energy from one transceiver site to another, at distances up to 1200 miles apart (Figure 11). Because these meteor trails last for only short periods of time (milliseconds to a few seconds), communication must be made using high speed digital data techniques. The statistical nature of the propagation path requires that a longer communications time window be allocated for any message exchange, compared with conventional VHF techniques.

In normal operation, one station (the Master Control Station on shore for this application) continually transmits a probe signal in the 40-100 MHz band.

When a propagation path is established via a meteor trail, the probe message will be reflected or reradiated (depending on meteor trail density) back to earth by an equal but opposite angle. If a transceiver is located within the probe message footprint area, the communications path is established. A brief exchange of status information is possible before the meteor trail disperses in the atmosphere thus severing the propagation path. The information exchange can only be assumed successful, then, if an acknowledge signal is received by both the MCS and ANP stations at the end of the exchange.

The frequency of meteors varies both seasonally and daily due to the changing orientation of the earth's surface with respect to the ecliptic plane and the earth's motion in it. A seasonal variation of about 4:1 can be expected, with a minimum in February and a maximum in August. Additionally, a daily variation also of about 4:1 can be expected, with a minimum at dusk and a maximum at dawn.

An AAN meteor burst system is represented in Figure 12. Each master control station would monitor up to several thousand ANPs, all located within 1200 miles of the transceiver antenna. The MCS would typically have a receiver and a 1000-1500 watt transmitter operating at about a 2k baud rate in the 30-50 MHz band. For much of the day, the station would poll its assigned aids, gathering and processing the status information sent in. After the nominal system polling is completed, those aids yet to successfully report in for the day would be polled again. After

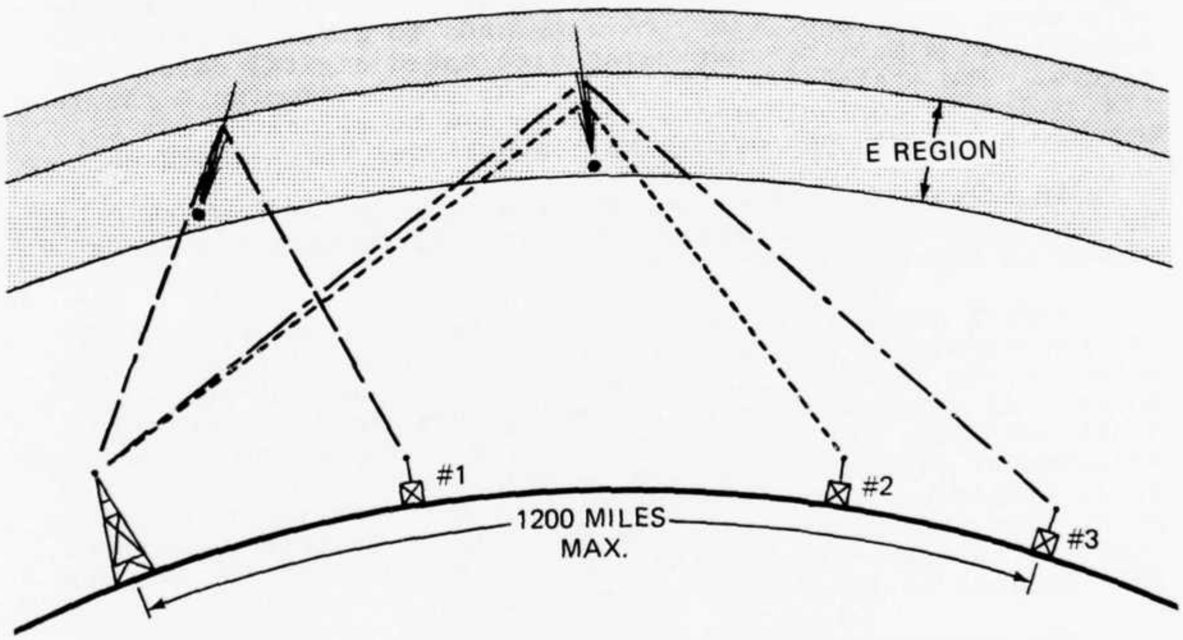


FIGURE 11 METEOR BURST COMMUNICATION LINKS.

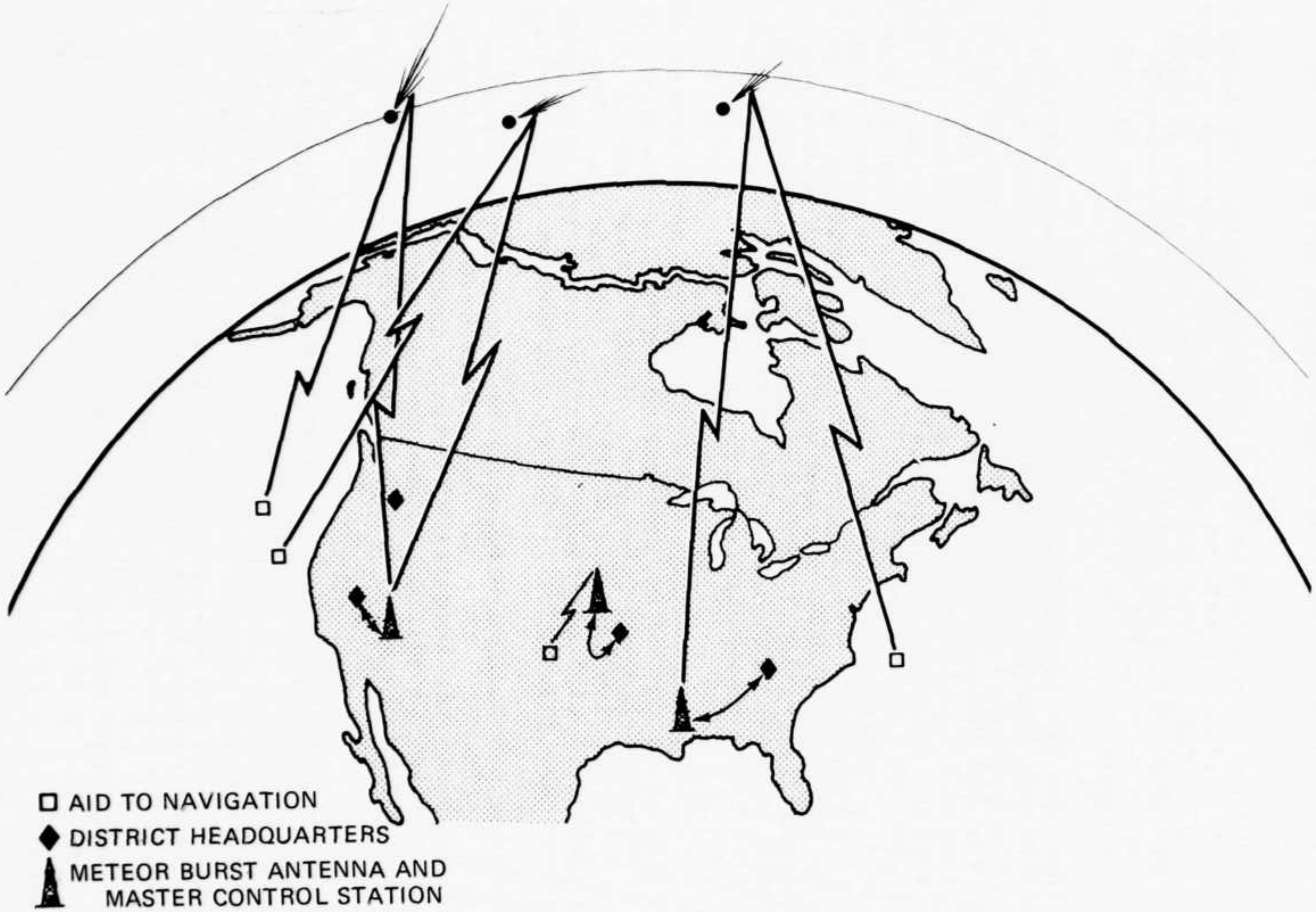


FIGURE 12 MASTER CONTROL STATION AND DATA DISTRIBUTION FOR METEOR BURST.

some defined interval, this directed polling would also be concluded.

The ANPs using a meteor burst communications link might have a transceiver capable of radiating 100 watts from an omnidirectional antenna. The low frequencies and signal polarization associated with this system will require that special attention be paid to the antenna design in the areas of size and signal gain.*

When the ANP transceiver is turned on, it will monitor the communications channel, waiting to detect a MCS probe signal via a meteor trail. If the signal contains an appropriate address, the ANP will send its status information and wait for an acknowledgment message containing a clock synchronization signal and the aid's address. Upon receiving the acknowledgment, the transceiver will be turned off. If no acknowledgment is received, the aid will continue monitoring the channel, waiting for it. Since no propagation path may appear, this signal may not arrive for some time. Likewise, the ANP might not even detect the original MCS probe signal within a reasonable length of time. Therefore, the ANP transceiver operation will have a time-out feature to avoid excessive battery drain.

As in the communication links, the meteor burst system will have periodic interrogate times set up during the day when the MCS can try establishing links with specific aids failing previously to respond or sending diagnostic information. This interrogate mode will not be as effective as in the other communications options, however, due to propagation uncertainties.

Polling sequences are directed by a computer controller unit within the MCS. This unit also generates ANP addresses, stores and processes incoming ANP status information, and sends the appropriate information to the various districts within its area of coverage via modem and phone lines (see Figures 13 and 14).

One possible configuration of Master Control Stations is shown in Figure 15. Even with only four stations in the continental U.S., there would be many areas of overlapping coverage. The intent of this configuration is to limit all the aids in a district to only one MCS, thus simplifying somewhat the lines of communication between Districts and MCS facilities. Separate stations would be dedicated to Alaska and Hawaii.

Meteor burst techniques have been known for at least thirty years; however, it is only recently that they have been employed

*Personal communication with Meteor Communications Consultants, Inc., Kent, Washington, 14 June 1981.

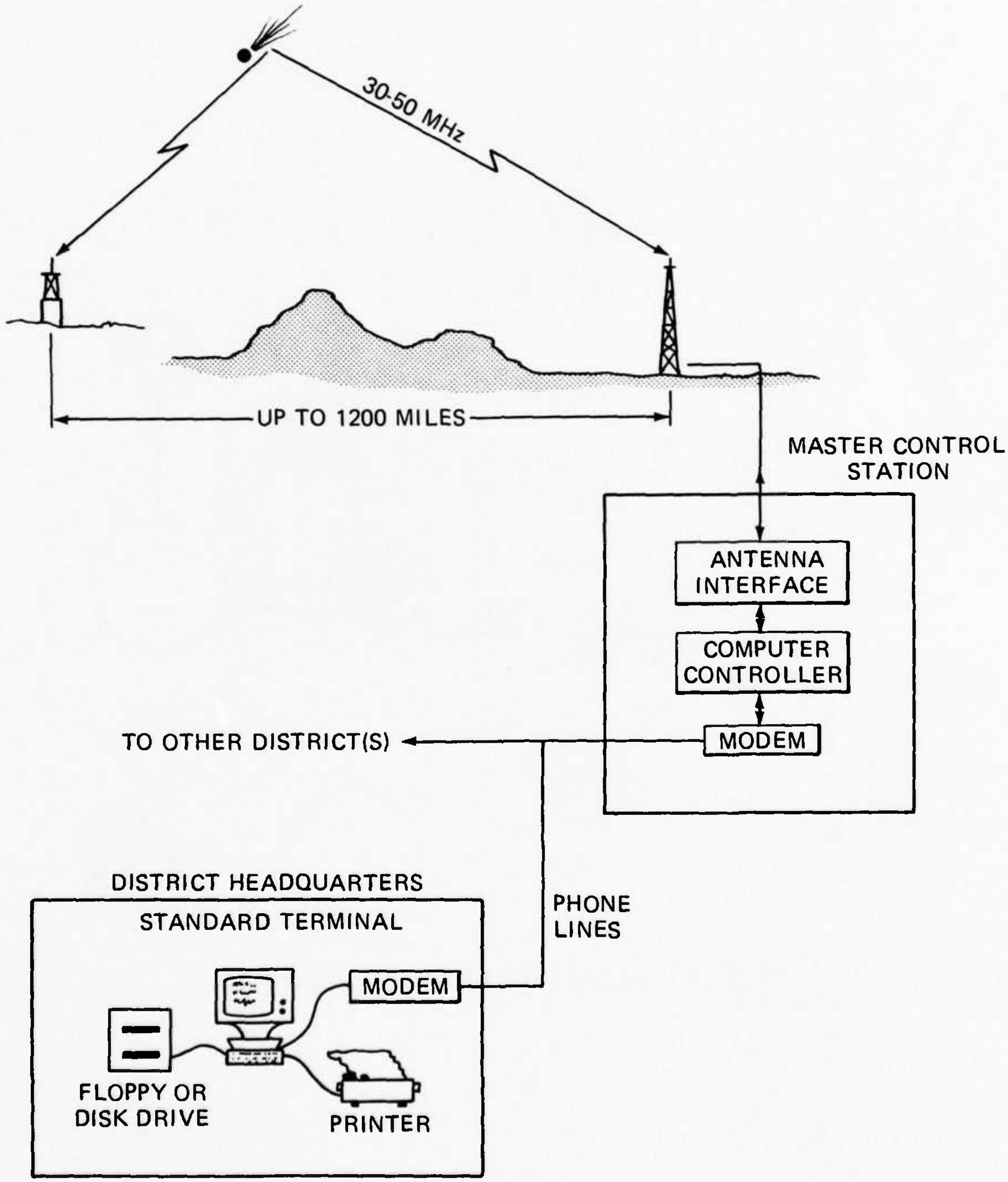


FIGURE 13 METEOR BURST MONITOR SYSTEM.

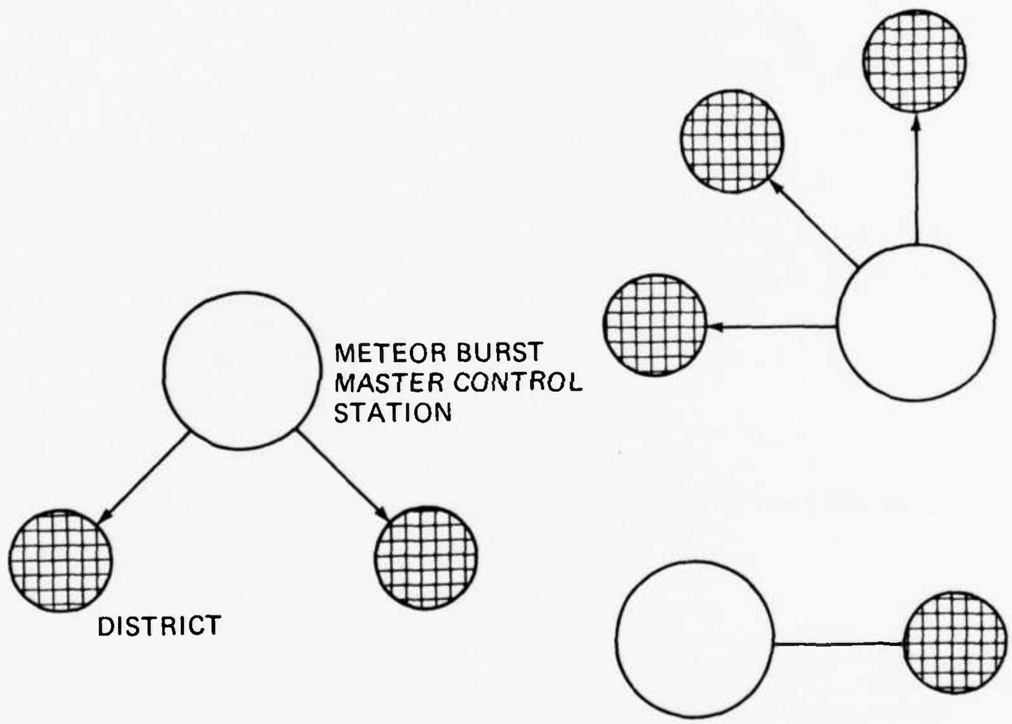
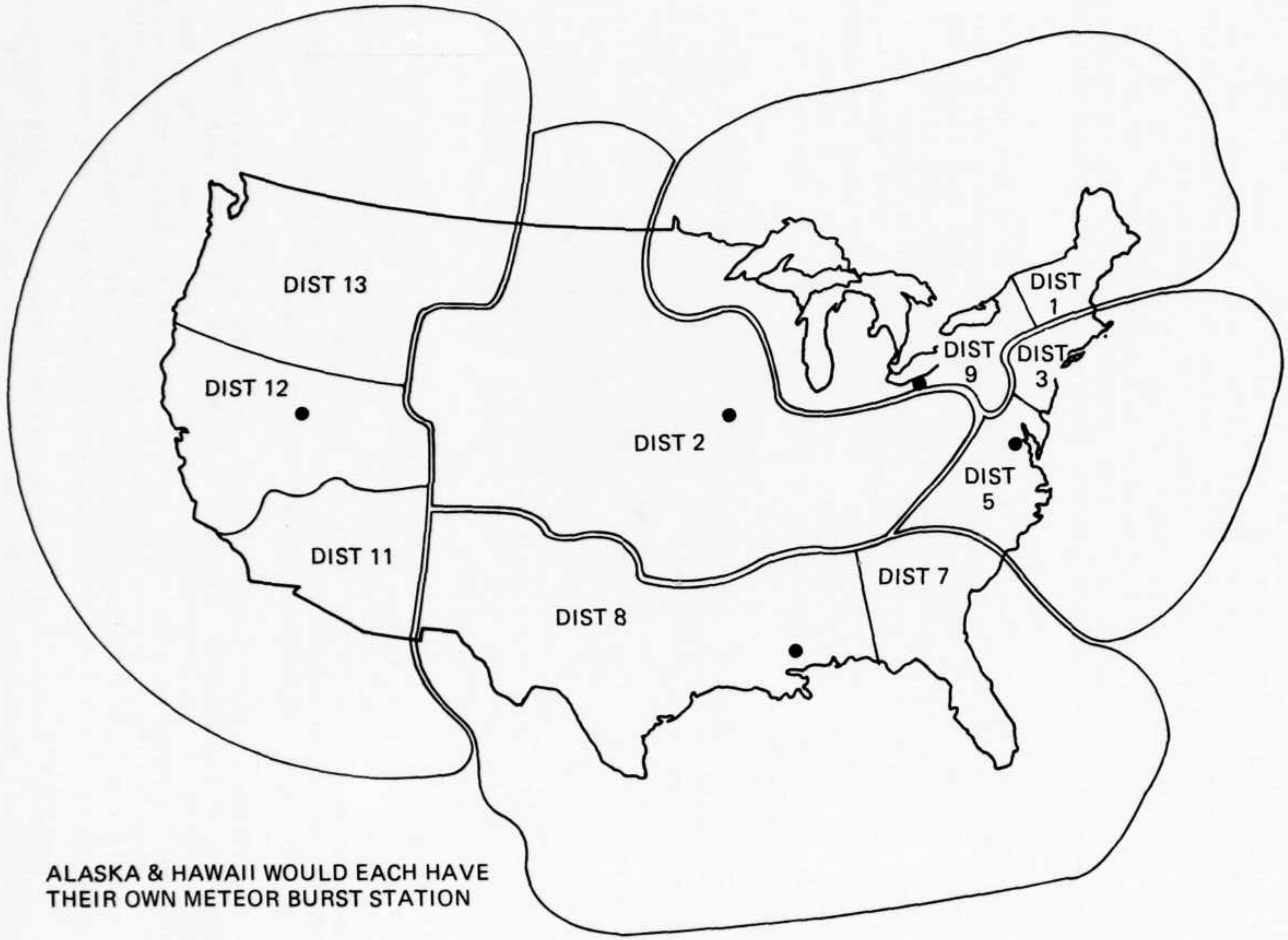


FIGURE 14 METEOR BURST DATA DISTRIBUTION.



ALASKA & HAWAII WOULD EACH HAVE
THEIR OWN METEOR BURST STATION

FIGURE 15 METEOR BURST COVERAGE.

in operational systems. One such system, SNOTEL, is operated by the Department of Agriculture in the Rocky Mountains. It is the largest meteor burst system built so far with about 500 remote data platforms and two master base antennas. Performance data have been collected since the system was activated in 1977.* Experience in the first two years of operation has shown that 85 to 95 percent of the operational sites have reported during the daily three hour nominal group morning polls. An average of 75 percent of sites polled ad hoc responded within 30 minutes of the request.

These figures describe a system that would be too unreliable for the Advanced Aid to Navigation Network. However, in discussions with people at SNOTEL,* it was learned that any installed site is considered "operational," so the figures also reflect equipment problems at the sites. Most recent indications are that, of properly installed and operating sites, 97% report back successfully in normal polling. It was estimated that the other 3% fail to report due to propagation problems; i.e., a meteor just didn't arrive in time, or interference got in the way of a successful link.

There are several types of channel interference that must be considered in a meteor burst system (see Figure 16). When a meteor passes through the atmosphere, it can create a propagation path to some location on the earth's surface. If only one ANP (such as P_c in Figure 16) was capable of receiving the resulting signal, no further poll addressing would be required. The status information could be sent back with no interference. However, the propagation path creates a signal footprint on the reception end measuring up to perhaps 50 miles in diameter. Any ANPs (P_B and P_A) in this area would also respond to the MCS's signal, thus interfering with each other.

Interference could also occur if two meteors simultaneously created propagation paths from different ANPs (P_C-T_1 and P_B-T_1) to the same Master Control Station. Similarly, two meteors could create propagation paths from one ANP back to two different Master Control Stations (P_A-T_2 and P_A-T_1), causing interference at the aid and erroneous data at the stations.

Because of this interference, the ANPs must be assigned separate ID addresses. The MCS's probe signal would contain this address, thus activating only one aid at a time. The time required to sequentially poll each aid in this manner could well prove prohibitive. A more efficient approach is to poll a group of widely separated aids simultaneously. Statistically, there should be little interference among aids since each aid would

*Personal communication from Manes Barton and Lloyd Vancil, Department of Agriculture, Watershed Forecasting Service, Soil Conservation Service, Portland, Oregon, 10 July 1981.

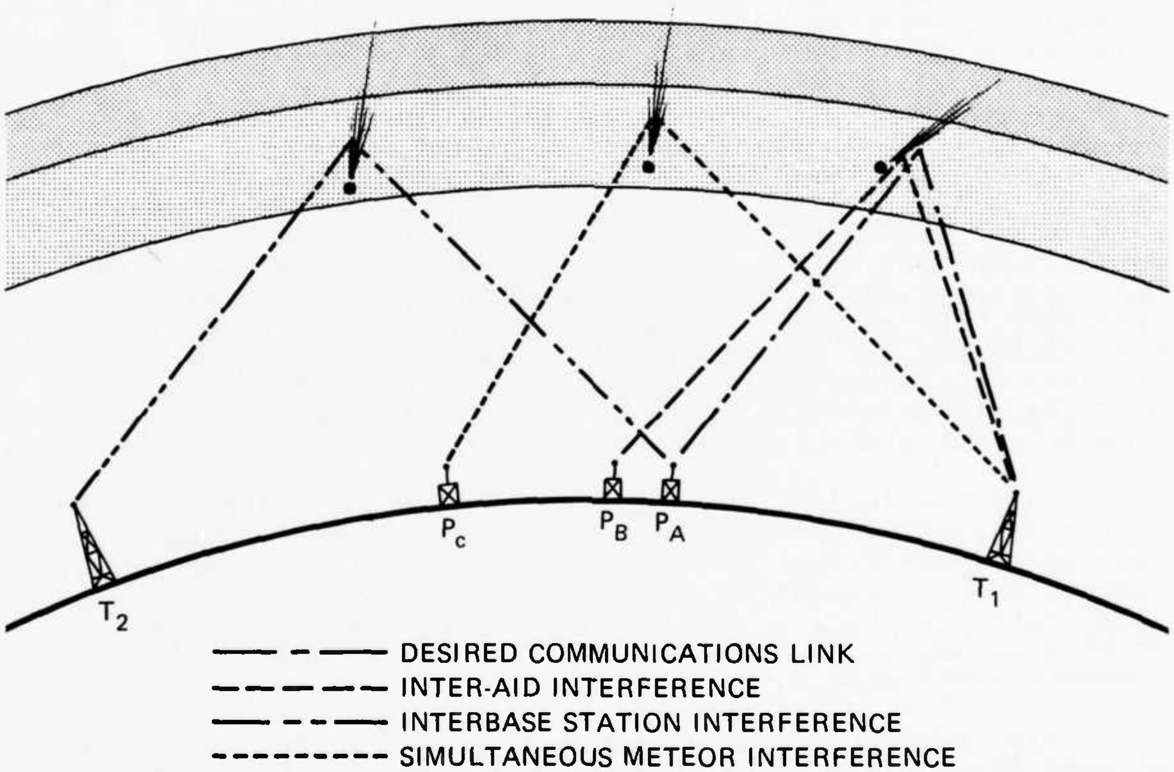


FIGURE 16 METEOR BURST INTERFERENCE.

require a different meteor trail to complete its link to the MCS. Using this approach, it should be possible to interrogate a group of 50 aids in approximately the same time required for two or three individually.

There are a number of ways to configure a meteor burst system to increase the throughput. To help eliminate the interference between neighboring ANPs, two different frequencies could be used on the ANP to MCS link. When neighboring aids detect the probe signal from the MCS, both could respond simultaneously on different frequencies. This would result in an average polling time of anywhere from the same to one-half of that for a single frequency link, probably closer to the latter.

Another way to eliminate local interference from many neighboring aids is to establish submaster stations. These stations would interrogate those around them via a standard line-of-sight VHF link. This information would then be sent back to the MCS using the meteor burst mode. This approach would reduce the effective number of burst channel users, and thus the interference. Although system throughput would be increased, the idea of a standard communication link will be stretched, and the equipment and software for the submaster stations would have to be designed and maintained. It is difficult to assess the desirability of this approach without more detailed aid placement information.

It is possible to incorporate a meteor burst approach within a conventional VHF system. The whole system would operate at some frequency between 40-100 MHz (VHF-meteor burst band). Most communication, either with ANP or ships, etc., would take place via a line-of-sight link. When a unit was located beyond line-of-sight range, the system would switch to a meteor burst mode.

This approach would be most beneficial if used as part of a coordinated command and control (C^2) network. As before, only six or seven antenna sites would be physically required to cover all U.S. waters, but since not all districts would have a meteor burst station, the C^2 information would necessitate real-time inter-district communication links. An alternate approach is to assign a meteor burst capability to each district, but this could result in inter-base station interference.

Just as in the conventional VHF option, the meteor burst VHF options give a high degree of flexibility and control to the Coast Guard. Access to the communications link is directly under its control, and modifications can be made to the system without concern for other users.

Obviously, one of the most important considerations is how often one can expect to successfully complete the communications

link between the MCS and its assigned aids, and at what data rate. Performance will vary with a number of parameters, including operating frequency, transmitter power, message length, receiver sensitivity, and antenna gains. Because of these factors, consistent numbers are difficult to find and it was beyond the scope of this study to determine them.

Estimates for a similar system were worked out by Meteor Communications Consultants*, and may give some indication of operating characteristics. The system would have a 1000-watt MCS transmitter and a 5-element, 12 dB antenna. The ANP would have a 100-watt transmitter using Bi Phase PSK modulation and a receiver sensitivity of -121 dBm with low index PSK. The data rate would be 2 or 4 kbps, and the antenna would have 2.2 dBi gain.

Based on these characteristics, the MCS and ANP would, on the average, establish a communication link every 2.76 minutes in the morning with 90% probability and every 7.2 minutes in the evening with 90% probability; these values are based on worst case February operation. Using such information, an AAN meteor burst system could be configured similar to the SNOTEL system. Because of the much larger number of remote locations involved with the AAN Network, it would be necessary to utilize a more sophisticated polling, antenna siting, transceiver, and data link approach to achieve the desired level of performance. All these areas would require further study before an overall system capability estimate could be made.

Although it should theoretically cause no problems, no one has implemented a marine meteor burst system. This factor. coupled with the development nature of the technology, lends a degree of technical risk to this approach.

Satellite Link

A satellite link offers the advantages of a reliable communications link and centralized AAN network processing. A number of options exist when configuring a satellite link--choice of using an existing satellite or building a new one, frequency band selections, and equipment selection.

In Appendix E, these and other factors are studied. After studying the requirements the satellite best suited to AAN needs is the GOES (Geostationary Operational Environmental Satellite) system operated by the National Environmental Satellite Service (NESS) of the National Oceanic and Atmospheric Administration (NOAA). The GOES system provides, free of charge to qualified users, a data relay service including

*Personal communication from Don Sytsma, Meteor Communications Consultants, 12 August 1981.

satellite and ground station equipment for brief environmental data messages. The "qualification" aspect will be discussed later.

All communications to and from the ANPs would be via the NESS Central Distribution Facility in Suitland Md. (see Figure 17). A current nationwide list of ANPs would be maintained in Suitland, where the satellite would be directed to individually monitor each aid daily. The aid would transmit its status message to the satellite, then resynchronize its onboard oscillator using a satellite-broadcast NBS time signal. The aid data would be transponded by the satellite to the Suitland facility, where it would be checked for parity, format, etc. Data errors or absences would be noted by the system for future corrective action. Information would then be sent to the appropriate Districts over phone lines via a Master Control Station (Figures 18 and 19).

During special time slots in the day, the communications link would change from a monitor mode to an interrogate mode. Every aid would process the satellite transmission, looking for its particular identification address. Once enabled, an aid could be instructed, for instance, to retransmit its status message. Limited capabilities could also be used to check the communications link on recently maintained or deployed ANPs. See Table 3 for details of this and other possible configurations.

The GOES communications link would be a low technical risk option -- NOAA, for example, presently uses the system to communicate with some 50 research buoys located off the U. S. coast. Hundreds of other users are also presently using the system to collect environmental data. With a signal acquisition probability greater than .999, the system also provides a very reliable means of data communication. In addition, hardware failures are minimized by satellite and ground equipment redundancy.

There are a few problems associated with this satellite approach. First, there would be no direct tie-in with the rest of the Coast Guard command and control network, meaning that both systems would not be directly integrated together over one communications system. This would not present serious operational difficulties, but it would mean that the Coast Guard would be responsible for maintaining two types of equipment: VHF equipment for their normal use and satellite equipment for their aid network. Because the ground equipment would not be operated directly by the Coast Guard, but rather by NESS, the Coast Guard would not have the flexibility and control of the network that they may desire. With careful scheduling, it would be possible to incorporate

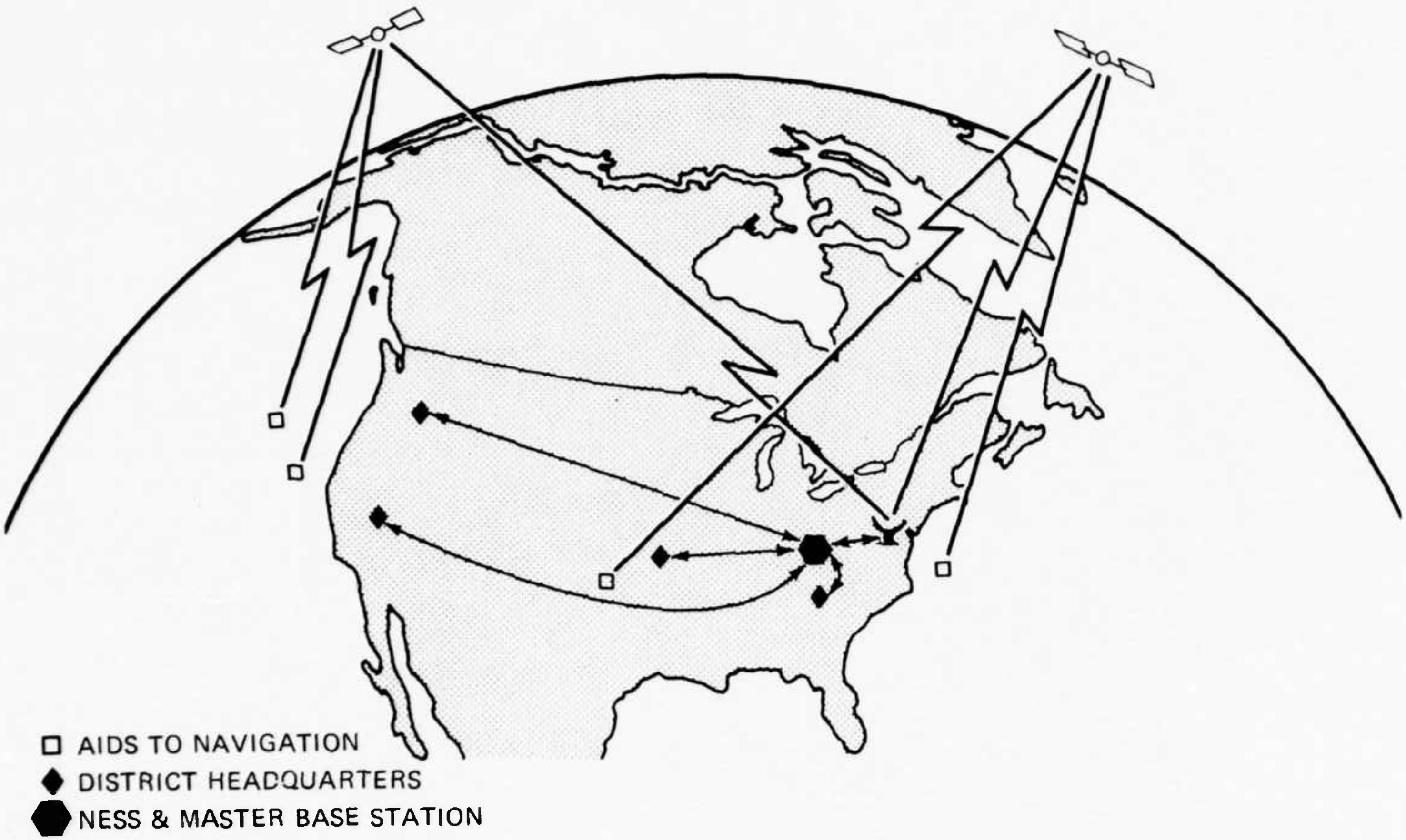


FIGURE 17 MASTER CONTROL STATION AND DATA DISTRIBUTION FOR GOES SATELLITE.

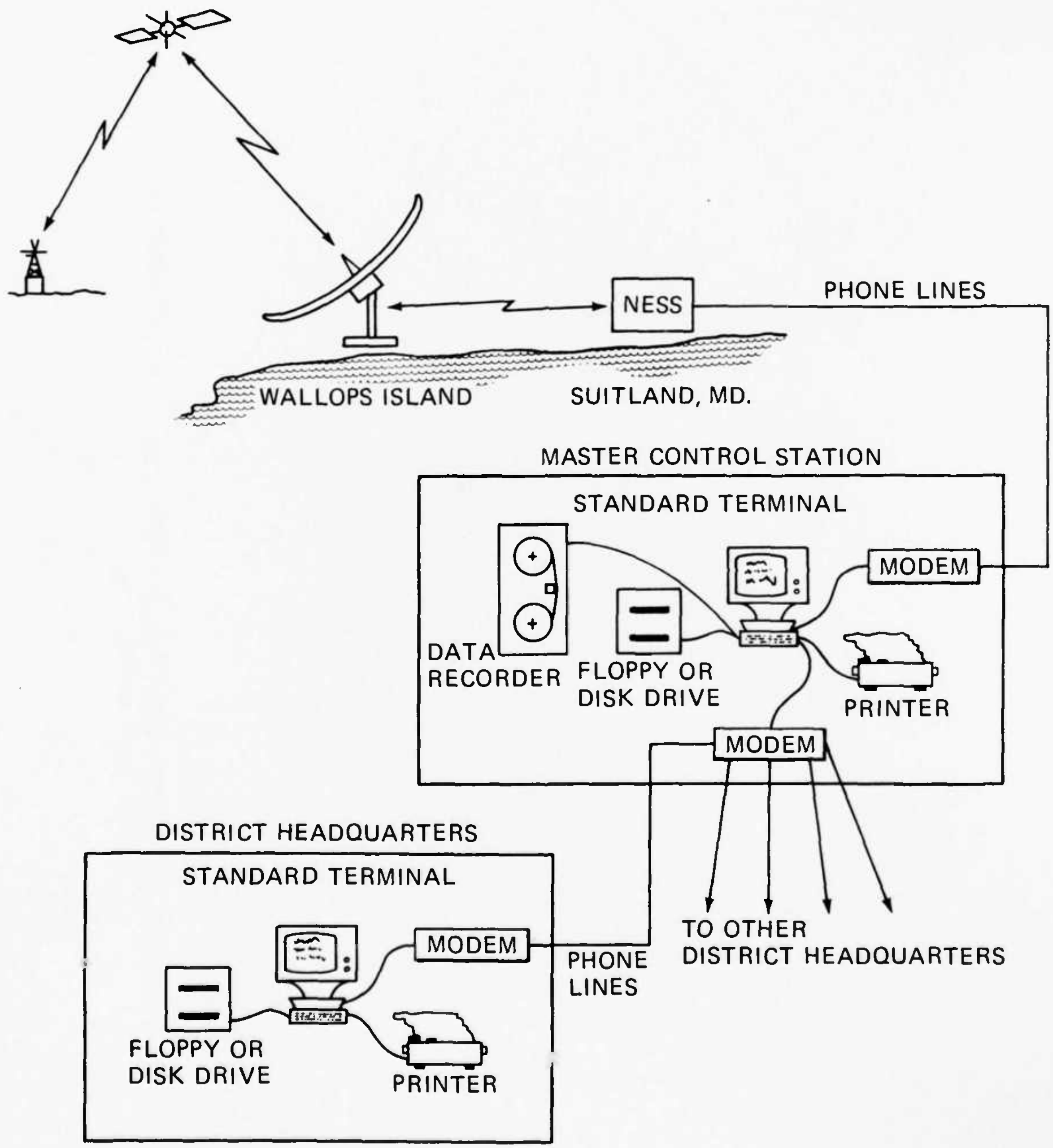


Fig. 18 SATELLITE MONITOR SYSTEM.

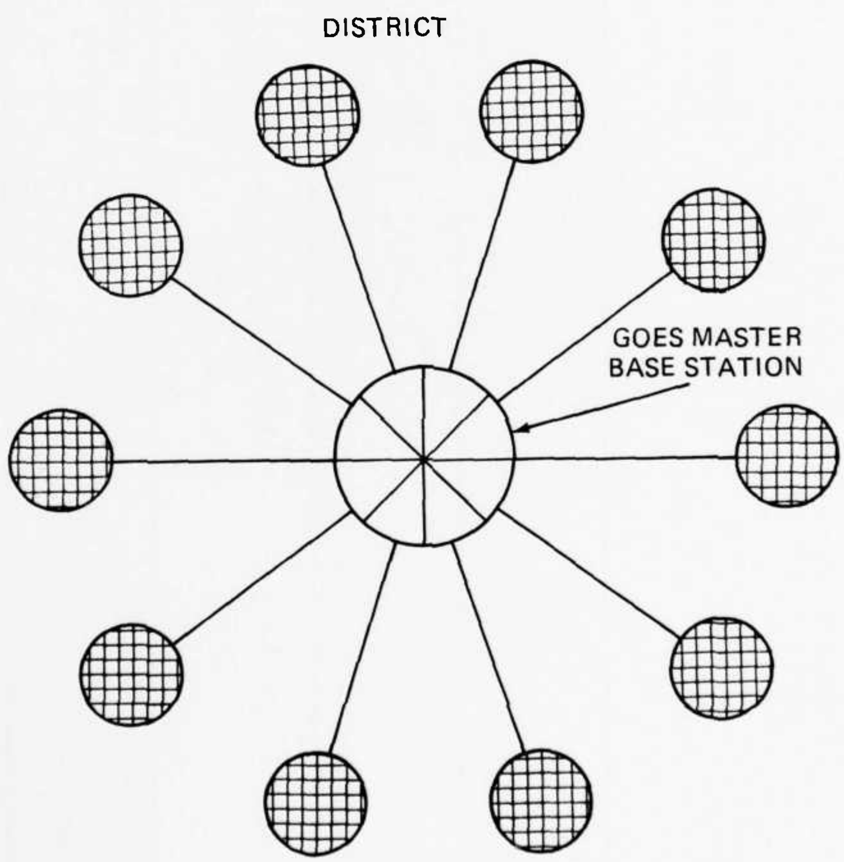


Fig. 19 GOES SATELLITE DATA DISTRIBUTION.

TABLE 3 - COMPARISON OF GOES REPORTING METHODS
(4 SEC MESSAGE ONCE/DAY; 20,000 BUOYS)

Method	Buoy Equipment Required	Number of Channels Required (full time)	Percent of Interrogation Channel Required	Buoy Timing Stability Required	Message Delay (as defined)
Interrogate	Single Freq. Xmtr., Receiver	1-2	5.5-11%	Negligible	1 day max., few seconds to any selected buoy
Self Timed	Single Freq. Xmtr., No Receiver	14	None	$2\text{-}9 \times 10^{-7}$/yr Must re-sync once every 1-5 years	1 day maximum
Satellite Timed	Single Freq. Xmtr., Receiver, Resettable Clock	1-2	None	$2\text{-}10 \times 10^{-6}$ for 6-24 hours propagation	1 day maximum
Random Reporting	Single Freq., Xmtr., No Receiver	12	None	The more random, the better	< 1 day 61% of time, < 5 days 99% of time
Proposed Hybrid (Sat. timed/ interrogate)	Single (possibly dual) Freq. Xmtr., Receiver, Resettable clock.	1-2	0.5-1%	10^{-5} over 6 hours	1 day maximum, 6 hours maximum to any selected buoy.

deployment, maintenance, and monitoring functions within the GOES network but it is not certain whether the Coast Guard can develop this kind of advanced scheduling.

Because the frequency band is in the higher UHF range, the ANP communications equipment for the GOES option would be more expensive than with the VHF option (see Cost Section). Also, because the equipment would be more complicated, it could be expected that it would be less reliable. Both these factors can be addressed further during the design stage. It would also be necessary to employ a separate communications antenna and Loran-C antenna due to the different frequency bands associated with each.

The UHF satellite to ANP interrogate frequencies allocated to the GOES system are shared with a "land mobile service," and since the GOES is the secondary user there may be an interference problem in urban areas, especially on the West Coast. This degree of interference is difficult to predict without actual experimentation. It is, therefore, an area requiring futher study.

The GOES system is primarily designed to handle small data collection platforms gathering environmental data. Because access to this system is limited to platforms collecting such data, it may be necessary to include some sort of environmental sensors on the aid platforms. The kind and quantity of data required to allow access to the system are not clearly defined at this time. It would require that the U.S. Coast Guard and NESS enter into a joint venture.

If the Coast Guard were allowed to use this system, it would by far be the largest single user. Although the system was not designed to collect data from operational systems, such as the AAN Network, the opportunity to increase the utilized capacity of the GOES Network may be desirable to NESS. In addition should the Coast Guard choose to operate its own reception station, these stations could possibly provide desirable backup to NESS.

There are a number of advantages for this communications option. Despite the ANP cost considerations associated with it, the GOES system could provide a reliable, low risk, moderate cost communications link for the Advanced Aid to Navigation Network and enhance the use of the satellite.

TIMEKEEPING REQUIREMENTS

The timekeeping accuracy requirement of the ANP oscillator is a function of the need to maintain flash synchronization and to turn the communications equipment on and off appropriately. Of these two functions, the flash synchronization has the

tighter specifications: no flasher may deviate more than 25 msec from its relative place in a chain flash pattern.

The oscillator must be able to maintain accuracy over the -23°C to +60°C temperature range with as small a power drain as possible. Maintaining the 25 msec accuracy plus a small safety margin is equivalent to requiring about 1 part per 10^7 accuracy per day. This could be met either with a very accurate oscillator or by synchronizing the clock periodically (daily perhaps) using a signal from an RF receiver.

A very accurate oscillator (.0001 PPM/day) will be fairly expensive ($2000) and would require a large current to maintain a constant temperature (100 mA). The clock would have to be initialized during deployment or maintenance activities. A less accurate oscillator (.1 PPM/day) will be less expensive ($50) and require less current to maintain a constant temperature (15 mA). Interface to the synchronization signal will be through the micro controller.

If the Coast Guard does not need to send commands to the ANP, the aid's synchronization device need not use the same communication system as its transmitter; one could use for instance the standard WWV signal or a marine broadcast occasionally modulated with timing pulses to synchronize the clock.

This alternate receiver concept would best apply to the GOES link option, where the receiver is a large part of the ANP equipment cost and the communications link is so reliable. The aid would typically have a UHF GOES transmitter for sending back status information, and a VHF or marine broadcast receiver to pick up synchronization signals for the clock.

Replacing the GOES receiver with one operating in a different frequency range would require the addition of another antenna to the ANP. It would also require the Coast Guard to operate two separate communications systems. By simplifying the design and producing in large quantities, the cost of the GOES receiver could potentially be made competitive with the other types of receivers.

Eliminating the command receiver in a GOES system eliminates the capability to interrogate specific aids. It would be necessary to either assume an unresponsive aid needed maintenance or wait until the next daily monitoring to try communicating with it again.

If flash synchronization is not incorporated into the Advanced Aid to Navigation Network, the accuracy requirement on the ANP oscillator may be eased somewhat. The new timing requirements will vary, depending on which communications option

is chosen. Satellite timing will still require a fairly accurate clock, unless a random reporting scheme is implemented. The standard VHF and meteor burst options will have fairly loose requirements since there is a larger communications time window available.

If we were to also eliminate the capability to interrogate specific aids or send commands, there would be no need to have any ANP communication receiver at all. An oscillator with an accuracy of about .001 PPM would be sufficient for these systems.

SHORE STATIONS AND DATA DISTRIBUTION

The previous section discussed some of the options in establishing a communication link between the ANPs and a shore station. The number of such stations will vary from option to option; one for a satellite link, and about 200 for a conventional VHF link. All these stations serve a similar function, however: collection and distribution of aid status data.

In conventional VHF or meteor burst links, a microcomputer will control the polling process, address codes, transmitted data, time signals, and special requests for interrogation. It will also monitor the received signal and check parity and encoding bits. The collected data will be sorted, stored, and eventually sent to the appropriate District Headquarters via phone lines on an automated callup modem.

The satellite link will already have a facility provided by NESS to handle much of the communications overhead. All the collected data will be forwarded to a central Coast Guard computer for sorting and distribution to District Headquarters. This electronic "mail sorter" is recommended to limit the number of Coast Guard-NESS interfaces to only one. All system additions, changes, etc., would be sent to NESS via this interface.

Only after the status data are received at the District Headquarters is the information processed to transform TDs into position and determine the operational status of each ANP. Assuming some hardwired math chip capability, a standard terminal should be able to process an aid in about 2 milliseconds CPU time. The data records would be structured to reduce the number of relatively slow storage medium accesses.

The computer's output would be a list of those aids reporting a problem or not reporting at all. Where possible, a short diagnostic message describing what sort of fault was detected would be included. Based upon this information, a decision could be made concerning how best to allocate the District's maintenance resources. The computer could be used to store pertinent information on each aid, such as location, type, and service record and print short service guides for the maintenance crews. This should help minimize the amount of recordkeeping associated with the AAN Network. Updates or additions to the District's aid network could be entered from a terminal in the District Headquarters. (Deployment and maintenance procedures will be described further in a later section).

POWER BUDGET

The aid to navigation platforms require power for four basic functions: the flashing light, control electronics, Loran-C receiver, and communications equipment.

Because the number of permutations of the various oscillator, control, and communication options is so large, the figures shown in Table 4 reflect only composite ANP configurations. However, most permutations apply to the communications area, which consumes relatively little average power, so the figures should be fairly representative.

Table 5 shows the power consumption for various size incandescent bulbs operated at 12 volts (nonextended lifetime). If reduced voltage techniques were used to extend lamp lifetime, the power consumption could be found with this table by using the data for the next larger bulb. Better matching of lamps to lighting needs and a larger selection of filament sizes would produce a large power savings with either normal or reduced voltage lighting.

The CMOS circuitry in the micro controller will be ON continuously, and will draw an estimated 3 mA current. The controller's sensors and control logic will have a very low duty cycle, and are estimated as a group to require 15 mAh/day. The CMOS oscillator will probably have to be temperature-controlled, and will therefore draw about 10 mA current in cold weather (when power is most scarce), or about 240 mAh/day. The power regulation circuitry consists of only a driver gate, a power field effect transistor (FET), and a shunt. Since the circuit will consume appreciable power only when shunting excess current, it is a negligible load on the battery.

The Loran-C receiver will draw about 15 watts power at 12 volts. Typical lockup time is about 5 minutes, with worst case being about 45 minutes on a few days per year. For average load considerations, the receiver will therefore require about 250 mAh/day.

The communications equipment power requirements are shown in Table 4 for the various options. The VHF and satellite transmitters will be ON for about 5 seconds per day. About half the meteor burst responses will be successfully acknowledged by the MCS, so a 10-second transmission is accounted for. The meteor burst receiver will also need to be ON about three times as long as the other options to detect the appropriate data. The GOES receiver requires 3-4 minutes to acquire the satellite's signal. Its 500 mA current draw could be reduced by specializing the design. All three options will have about 15 minutes of interrogate mode operation per day.

As shown in Table 5 assuming the use of an incandescent lamp, the total daily electrical load on the ANP battery will, under worst case conditions, be below 5.2 Ah for 97% of the aids deployed.

TABLE 4 - ANP POWER BUDGET

LOAD	VHF	METEOR	SATELLITE
Light	Between 1.5 & 4.3 Ah/day for 97% of aids.		
Electronics Microprocessor System Oscillator Regulator Sensors & Control	 3 mA x 24 hr - 72 mAh 10 mA x 24 hr (worst case) - 240 mAh Negligible 15 mAh - covers peripheral control circuits, sensors, etc.		
Loran-C Receiver	15 watts x 20 min/lockup x $\frac{1\text{ watt}}{12\text{ volts}}$ x $\frac{1\text{ hr}}{60\text{ min}}$ = 250 mAh		
Status Transmitter	1.2 A x 5 seconds x $\frac{1}{3600}$ = 2 mAh	100 watts x 10 seconds x $\frac{1}{3600}$ x $\frac{1}{12}$ ÷ .3 effic.= 75 mAh	40 watts x 5 seconds x $\frac{1}{3600}$ x $\frac{1}{12}$ ÷ .3 = 15 mAh
Cmd or Sync Receiver	15 mA x 25 min x $\frac{1}{60}$ = 6 mAh	20 mA x 60 min x $\frac{11}{60}$ = 15 mAh	500 mA x 7.5 min x 4 times/day x $\frac{1}{60}$ = 250 mAh
Electronics Sub Total	585 mAh/day	667 mAh/day	842 mAh/day
TOTAL	2.1 to 4.9 Ah/day	2.2 to 5.0 Ah/day	2.4 to 5.2 Ah/day

TABLE 5 - USCG DISTRIBUTION TABLE OF EFFECTIVE LAMP POWER REQUIRED

FOR VARIOUS LAMP SIZE - DUTY CYCLE COMBINATIONS*

Lamp Size (Amperes)		Duty Cycle (%) 10	12	16	18	30	33	50	75	Total % of Aids
	Ah	.352	.434	.563	.650	1.08	1.11	1.64	2.46	
.25 %		6.10	.33	5.2	.07	1.10	.59	.38	.01	= 13.78
	Ah	.807	1.00	1.29	1.495	2.49	2.48	3.63	5.45	
.55 %		37.80	6.80	1.9	.70	7.03	.04	2.20	.04	= 56.51
	Ah	1.162	1.242	1.86	2.143	3.572	3.500	5.102	7.653	
.77 %		11.48	2.7	.09	.43	2.18		.56	.06	= 17.50
	Ah	1.79	2.215	2.870	3.322	5.54	5.32	7.67	11.505	
1.15 %		6.3	1.22	.08	.31	1.73		.518		= 10.16
	Ah	3.41	4.305	5.45	6.46	10.76	9.57	13.65	20.475	
2.03 %		1.16	.18	.02	.05	.13		.13		= 1.67
	Ah	-	6.47	8.63	-	-	14.67	20.605	30.91	
3.05 %		.29								= .29
TOTAL %		63.13	11.23	7.29	1.56	12.17	.63	3.79	.11	99.91

Ah = Ampere-hour load imposed on battery in one day assuming 13 hour flash operation per day.

% = percentage of aids in this category based on NOV 1979 SANDS Run showing 14082 Minor Aids to Nav.

*Produced by U.S. Coast Guard Office of Engineers.

Referring to Figure B-5 in Appendix B, it can be seen that this load could be supplied by a 35 watt solar panel and a 300 Ah battery.

The other 3% of the aids require between 4.3 and 13.65 Ah to power the larger incandescent lamps. With a sufficiently large battery (up to about 1200 Ah), these aids could be adequately powered using a 70-watt panel. It is likely the power consumption can be reduced on much of the electronic circuitry by custom designing the equipment. However, the greatest power savings will be gained by making the light source more efficient.

DEPLOYMENT AND MAINTENANCE

There are two occasions when a Coast Guard crew will visit an aid-to-navigation location; when the aid is first being deployed or when it requires maintenance. In both cases, the objective is to leave behind a correctly positioned and operating ANP.

A deployment crew will typically bring an aid, diagnostic tester, and the appropriate initialization information to the deployment site. The aid will be positioned using standard methods, i.e., sextent, visual sitings, Loran-C (if site is already surveyed), etc. The final Loran-C coordinates of buoys and monitors will be either manually or automatically recorded for entry into the District computer. Upon power up, the aid will begin executing an initialization routine, clearing various flags and registers, and enabling the communications link. When the aid is ready to be initialized, the diagnostic tester will be attached to the ANP electronics package through the lamp connector via an "umbilical" cord. The tester will transfer the following previously entered data to the aid:

1) Time of day (accuracy varying from 1 second to tens of minutes, depending on communications link)

2) Communications time slot

3) ANP ID address code

4) Flash pattern type and position

By reading various connections via the backplane, the aid can determine whether there is a Loran-C receiver or lamp assembly, and configure its software appropriately.

The aid will be instructed to test its Loran-C receiver (if there is one), flash its lamp in proper sequence, and report the system status via the RF link. The diagnostic tester, with its own attenuated RF transceiver, can be used to check the data and send an acknowledgment. GOES can, in addition, give a complete round trip communication link test. Following the tests, the service crew will complete the aid installation, assured that the aid is working properly. Data concerning the ANP installation will be saved for transfer to the District computer.

Servicing a deployed aid is similar to the process described above, except the crew must also be able to diagnose and repair malfunctions on the aid. To this end, they will bring a suitable selection of replacement modules to the aid site.

Assuming the ANP was able to report its problem over the RF link, the repair crew will already have a good idea what needs to be done to the aid. However, it is impossible to build an on-board diagnostic system that is infallible since the system cannot be sure that its sensors are not malfunctioning. Some problems, such as a burned out lamp or stolen solar array, are obvious, and can be immediately addressed. Problems internal to the electronics package, or loose connections, however, are not always so easy to diagnose. For this reason, the crew will also use the diagnostic tester described above.

In this case, the tester will be directly connected to the battery, flasher, and solar array. Operating parameters will be measured automatically, and a go no-go indication will be produced. If the problem is still not identified, the electronics package will be removed and replaced with another, similar package. No attempt will be made to repair the old package at this time; it will be brought back with the service crew for depot-level repair. The new electronics package will be initialized and tested as in a deployment operation.

SYSTEM RELIABILITY

One of the major design goals for the Advanced Aid to Navigation Network is to realize a meantime between maintenance for the aids to navigation of about 5 years. It is therefore important to predict what kind of reliability will be attained with the proposed addition of various electronic circuit modules.

ANP RELIABILITY

Table 6 shows meantime before failure (MTBF) figures for the various modules of the ANP. It was extremely difficult getting MTBF figures from manufacturers concerning existing product lines, let alone a new design. Therefore, the figures shown are often estimates based on parts count or informed "guesstimating."

It should be noted that very few manufacturers thought the 5-year MTBF would be easy to achieve. It may be necessary to use military grade components, design in redundant circuitry, and/or use burn-in acceptance procedures to achieve the desired reliability.

The unprotected marine environment can be quite harsh on connectors, cabling, etc., but the 5-year goal for mechanical components is realizable without excessive cost. The greatest area of concern here is the solar array. It is assumed that the required testing on array performance and lifetime is being handled by the Coast Guard.

The reliability of the ANP is one of the largest drivers in this project. To increase MTBF from 2-1/2 to 5 years, for example may mean a factor of 3 increase in price for the electronic circuitry, depending on the reliability approach taken. Because this area will have a major impact on the technical and economic feasibility of the project, it will require more effort to obtain firm reliability estimates.

SHORE BASE RELIABILITY

The reliability of the shore-based Master Controller Stations and District processing facilities is not as large an economic driver as that of the ANPs because of the relatively few stations required. Redundancy could be built into the system both at the transceiver sites and at the Districts. Since most of the equipment will be located in benign environments, and can receive regular maintenance servicing, it will be less likely to fail.

The phone data-link equipment will likewise be fairly easy to maintain and operate. Data can be stored temporarily at the Master Controller Stations should the data link temporarily be unavailable for transmission of aid status information.

TABLE 6 - ANP RELIABILITY PROJECTIONS

Module	Projected MTBF	Source
Loran-C	2.5 years	Internav Inc.
Light	6 years	GE - 1
Command Transceiver		
VHF	7-8 years	Communitronics - 2
GOES	5 years	LeBarge - 3
Meteor Burst	2.3 years	MCC - 4
Micro controller	5.2 years	APL - 5
Battery	at least 5 years	APL - 6

MTBF estimate based upon:

1. Six-lamp assembly with S-11 incandescent lamps running at reduced voltage.
2. Operational experience and MTBF calculations for similar equipment.
3. Operational experience with similar equipment.
4. Study by Meteor Communications Consultants on an MCC-540 terminal, assuming 100% duty cycle except for transmitter, 25° C, environmental factor of 2 using Mil. Std. 217B - commercial grade parts.
5. Parts count calculation, commercial grade parts.
6. Allen, W. H., "Design and System Level Performance of a Battery Charge Regulator for Solar Photovoltaic Powered Aids to Navigation," JHU/APL, CP-083, Aug. 19, 1981.

COST ESTIMATES

The costs for the various elements of the independent VHF, piggyback VHF, meteor burst, and GOES satellite systems are shown in Tables 7 through 13. The pricing assumes a purchase lot of 1,000 ANP systems.

The two major cost items on the ANP are the communications transceiver and the Loran-C receiver. The Loran-C price of $1,000 is based on a modified Internav LCM 403 receiver board (no display, keyboard, or receiver housing). It may be possible to reduce this price further by using the microprocessor already present in the aid to supply the necessary control intelligence to the receiver.

VHF EQUIPMENT

Transceiver equipment prices vary widely, depending on the communications option chosen. The VHF price is based on approximate quotes from Communitronics Ltd. and Refraction Technology Corporation for 5 watt marine VHF transceivers. Price quotes were given on quantities of 1000 for Communitronics equipment, indicating substantial savings over other manufacturers. Further price information will be necessary once this link is better defined.

METEOR BURST

Meteor burst transceiver prices are based upon a price quote from Meteor Communications Consultants. The price estimate was $500-$1,000 for quantities of 15,000. Table 10 assumes $1,000 due to the smaller lot being quoted and uncertainties in the price quote.

GOES SATELLITE

The GOES transceiver estimate is based upon a $2,700 unit price quote from Communitronics for the transceiver unit including an NBS time receiver. A conservative 25% discount was applied to this equipment. It should be noted that the price of a GOES satellite transceiver is much higher than the other options due in large part to the small quantities presently being built. One can expect that a large quantity purchase of such equipment would not only earn the usual discounts for quantity, but also drive the whole GOES equipment market down in price.

Customizing the design for this application could also prove financially beneficial; such a design, however, was beyond the scope of this effort. Producing a customized GOES transceiver in large quantities could bring the price of the GOES options down to the point of being competitive with the meteor

TABLE 7 - NONRECURRING COST FOR ANP ELECTRONICS
WITH VHF LINK

BUOY ELECTRONICS (1000-pc Lot)	Fixed	Moored	ANTENNA SITE	Additional Transceivers	Piggyback
Antenna, Coupler, Duplexer	$ 50	$ 50	VHF Transceiver	$7,000	$ 0
Loran-C Monitor Receiver	--	1,000	Antenna & Filter	300	0
Command Receiver	70	70		7,300	0
Micro Controller	150	150	MASTER CONTROL STATION		
Transmitter	110	110	Audit & Data Acquisition Control Unit	4,000	4,000
System Integration & Testing	200	200	Modem	500	500
			System Integration & Testing	1,000	1,000
TOTAL ESTIMATED COSTING	$ 580	$ 1,580	TOTAL ESTIMATED COSTING	$5,500	$ 5,500

Assumes specification prepared and initial development done during experimental phases.
Does not include nonrecurring post-experiment costs.
Does not include cost of system documentation beyond that provided with standard commercial equipment.
Does not include cost of creating or editing ANP data files.
Does not include installation or system software costs.

TABLE 8 - NONRECURRING COST FOR EQUIPMENT
AT DISTRICT HEADQUARTERS

DISTRICT BASE STATION (10-pc Lot)	
Modem	$ 500
Microcomputer Data Base Terminal (could be replaced with District computer)	0 - 3,500
System Integration & Testing	1,000
TOTAL ESTIMATED COSTING	$1,500 - 5,000

Assumes specification prepared and initial development done during experimental phases.
Does not include nonrecurring post-experiment costs.
Does not include cost of system documentation beyond that provided with standard commercial equipment.
Does not include cost of creating or editing ANP data files.
Does not include installation or system software costs.

TABLE 9 - NONRECURRING SYSTEM COST WITH VHF LINK

	Independent VHF Each	Independent VHF All	Piggyback VHF Each	Piggyback VHF All
ANP Electronics				
- Fixed (10,000)	$ 580	$ 5,800,000	$ 580	$ 5,800,000
- Moored (5,000)	1,580	7,900,000	1,580	7,900,000
Master Control Station (60)	5,500	330,000	5,500	330,000
Antenna Site (200)	7,300	1,460,000	0	0
District Base Station (12)	5,000	60,000	1,500	18,000
Total		$15,550,000		$14,048,000

Assumes 1/3 of aids are moored.

TABLE 10 - NONRECURRING COST FOR ANP ELECTRONICS
WITH METEOR BURST LINK

BUOY ELECTRONICS (1000-pc Lot)	Fixed	Moored	MASTER CONTROL STATION (6-pc Lot)	
Antenna, Coupler, Duplexer	$ 50	$ 50	VHF Transceiver	$ 9,000
Loran-C Monitor Receiver	--	1,000	Audit & Data Acquisition Control Unit	7,500
Command Transceiver	1,000	1,000	Modem	500
System Integration & Testing	200	200	System Integration & Testing	2,000
TOTAL ESTIMATED COSTING	$1,400	$2,400		$19,000

Assumes specification prepared and initial development done during experimental phases.
Does not include nonrecurring post-experiment costs.
Does not include cost of system documentation beyond that provided with standard equipment.
Does not include cost of creating or editing ANP data files.
Does not include installation or system software costs.

TABLE 11 - NONRECURRING SYSTEM COST WITH METEOR BURST LINK

	Independent Meteor Burst each	all
AAN Electronics		
- Fixed (10,000)	$ 1,400	$14,000,000
- Moored (5,000)	2,400	12,000,000
Master Control Station		
- (6)	19,000	114,000
Antenna Site		
- (6)	20,000	120,000
District Base Station		
- (12)	5,000	60,000
Total		$26,294,000
Assumes 1/3 of aids are moored.		

TABLE 12 - NONRECURRING COST FOR ANP ELECTRONICS WITH GOES SATELLITE LINK*

BUOY ELECTRONICS (1000-pc Lot)	Fixed	Moored	MASTER CONTROL STATION (1-pc Lot)	
Antenna, Coupler, Duplexer	$ 300	$ 300	Data Recorder	$ 1,000
Loran-C Monitor Receiver	-	1,000	Data Distribution & Storage Control Unit	15,000
Command Transceiver	2,000	2,000	Modems	1,000
Micro Controller	150	150	System Integration & Testing	3,000
System Integration & Testing	200	200		
TOTAL ESTIMATED COSTING	$ 2,650*	$3,650*		$20,000

Assumes specification prepared and initial development done during experimental phases.
Does not include nonrecurring post-experiment costs.
Does not include cost of system documentation beyond that provided with standard commercial equipment.
Does not include cost of creating or editing ANP data files.
Does not include installation or system software costs.

*Refer to satellite transceiver section of the Cost Estimates.

TABLE 13 - NONRECURRING SYSTEM COST WITH GOES SATELLITE LINK

	each	all
AAN Electronics		
- Fixed (10,000)	$2,650	$26,500,000
- Moored (5,000)	3,650	18,250,000
Master Control Station		
- (1)	20,000	20,000
District Base Station		
- (12)	5,000	60,000
TOTAL		$44,830,000*

Assumes 1/3 of aids are moored.

*Refer to satellite transceiver section of Cost Estimates.

burst and VHF options. The price estimate for the satellite option is therefore the most uncertain.

Prices quoted for the antenna sites are based on telephone conversations with the Coast Guard Headquarters and with Meteor Communications Consultants. A large part of the master base controller costs will be the system programming and aid data base generation. These figures were not estimated.

Prices for computer systems were estimated based upon the mini-to-micro-computer market. A substantial increase in computer power requires very little additional capital expenditures, so the figures should be fairly accurate.

Solar arrays, batteries, and support platforms were not included in the cost estimates. Also excluded are the costs of the cabling and the waterproof electronics package container. These items are not dependent upon the choice of communications options, and can be added in as a constant.

Both the ANP and base station cost estimates assume that detailed equipment specifications have been prepared and initial development costs have been carried during the experimental phases, and, when required, in a post-experimental development program.

Table 14 summarizes the communication link costs and technical considerations.

TABLE 14 - COMPARISON OF COMMUNICATIONS LINKS

Consideration	Conventional VHF	Meteor Burst VHF	GOES Satellite
Technical Risk	Low; communications link is straightforward, though data distribution is fairly involved.	Medium; interference and propagation problems may make communications link too unreliable over short periods.	Low; communications link is proven, data distribution is straightforward.
Frequency Band	Standard VHF communications channel 168-175 MHz	Low VHF communications channel 30-50 MHz.	UHF communications band 402 MHz and 469 MHz.
Frequency Allocation Required	No, unless a separate VHF channel approach is taken.	Yes	No
Supports Semi-Random Interrogation	Yes	Marginal - interrogation may go unanswered due to propagation medium.	Yes
Tie-in with proposed CG Command & Control System	Yes	Yes, if VHF communications are moved to 30-50 MHz band.	Not a candidate
Cost/Aid	$580 - 1,580	$1,400 - 2,400	*
Cost/Master Control Station	$5,500 - $12,000 (60 each)	$19,000 (6 each)	$20,000 (1 each)
Major Equipment Development	Upgrade required in Coast Guard C^3 System	No	Customized design for aid transceiver; could reduce price significantly.

*Refer to satellite transceiver section of Cost Estimates, p.57

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. The largest power consumer on an aid to navigation is the light source; therefore significantly reducing the power requirements of the aid necessitates the use of a light source more efficient than the present incandescent lamp.

2. The most viable light source presently available is still the tungsten-filament incandescent bulb, for reasons of cost, efficiency, availability, and operating characteristics. Xenon flashtubes also look promising if run in a "flicker mode" to approximate a continuous signal.

3. The power system will be comprised of a 12-volt rechargeable lead-acid battery, a solar array (except possibly in a few locations such as Alaska), and a CMOS microprocessor-based micro controller module. The micro controller will employ a ripple-shunt regulator to prevent overcharging despite changes in power load or weather conditions. Most aids (97%) will require at most a 35 watt solar array with a 400 Ah battery.

4. In addition to regulating the power system, the micro controller will also direct the flasher, positioning, communications, and diagnostics systems on the aid to navigation platform. Aids will be capable of formulating a status message describing the position and system performance for the previous 24 hours of operation. This information will be sent to a Coast Guard shore station once per day; additionally, the aid will enter an interrogate mode once every 6 hours for a possible shore initiated information exchange.

5. A differential Loran-C system is capable of providing the desired 30 meters positioning accuracy. TD information will be processed on shore.

6. The ANP will require a command receiver to achieve synchronized flashing; a time signal will be sent via this link to each aid at least once per day. This link also makes it possible to poll each aid sequentially for its status, and send commands to the aid network. The ANP will also require a status transmitter to send the status of the aid back to a shore station and eventually the appropriate District Headquarters.

7. Of the three communications options studied -- conventional VHF, meteor burst VHF, and the GOES satellite system -- all seem technically capable of serving as the link between the

ANPs and the District Headquarters. Meteor burst VHF is the least attractive approach, due to the moderate degree of technical risk, unreliability of the communications link, and costs. Conventional VHF is the most attractive approach in that it can be incorporated within a unified command, control and communications Coast Guard VHF system. Assuming such a system is built, very little additional shore equipment will be required to include the aid network. If built on its own, the aid to navigation VHF system will still be an attractive option due to its reliability, relatively low cost, and low technical risk. Lastly, the GOES satellite system is attractive because of the very reliable communications link and simple data processing and distribution system it makes possible. The system's major drawback is the presently high cost of ANP communications equipment. Because these costs are due primarily to the very limited number of GOES transceivers being built now, it is quite possible that a customized design built in large quantities could compete with the VHF option.

8. Cost savings for the Advanced Aid to Navigation Network could be realized if the Coast Guard is willing to do without various aid capabilities:

   (a) Doing without position monitoring on buoys will save the cost of a Loran-C receiver per buoy. This would result in a system savings of approximately $5 million (5000 buoys x $1000/buoy) plus a small savings in system programming, monitors, and maintenance. It would also shorten the status message substantially, requiring less communications time.

   (b) Doing without synchronized group flashing on aids will remove the largest requirement for having a command receiver on the aids for a conventional VHF or GOES link (meteor burst requires a transceiver by nature). Also lost would be the capability of interrogating a specific aid or sending commands. This would save about $1 million for a VHF system and about $17 million for a GOES satellite system. Because there would be no timing signal to resynchronize the ANP clock, however, it might be necessary to go to more than one GOES channel in a "random reporting" approach.

   (c) Doing without a communications link would necessitate giving up the capability for remote diagnostic and position monitoring. The result would essentially be the present aid with a rechargeable power supply. Practically all the electronics, communications, and processing costs would be saved by this approach. The money could be used instead to develop more reliable and longer lasting

light and power sources and position maintenance equipment.

RECOMMENDATIONS

1. Because of its major impact on the battery and solar array requirements, the light source deserves further study. Specifically, further investigation should be carried out on:

   (a) The actual lighting needs of present aids with the goal of specifying less powerful lamps where possible.

   (b) The relative merits of procuring and using intermediate lamp sizes to better match actual light requirements and outputs.

   (c) The failure modes of the present aid light system.

   (d) The relative merits of operating the tungsten filament incandescent lamps at a reduced voltage level to improve lamp lifetime.

   (e) The design features of a flashtube operated in a "flicker mode"; i.e., the flicker rates required, the brightness required of the light pulses, the efficiency of the process, etc.

2. A design study should be performed for a GOES transceiver unit to determine the minimum purchase cost of a suitable unit, when produced in large quantities.

3. Preliminary discussions with the National Environmental Satellite Service (NESS) should be instituted to determine the desirability of a joint Coast Guard - NESS GOES venture.

4. To determine the cost effectiveness of implementing an Advanced Aid to Navigation Network (or making any changes at all to the present aid network), operating costs should be differentiated for maintaining the present aid network.

5. The impact of the proposed ANP equipment reliability goals merits further study; specifically, tradeoffs between MTBF requirements, system cost and performance need to be investigated.

ACKNOWLEDGMENT

The authors wish to acknowledge the contribution of R. G. Hires for his survey of light sources, J. E. Tarr for his work on diagnostic and control circuitry, and M. C. Chiu for her oscillator investigation. J. F. Harrison and J. G. Wall provided technical guidance and program direction throughout the course of this feasibility study.

Technical contributions were also made by Bill Mazur (NESS) on the GOES satellite system, Lloyd Vancil (Dept. of Agriculture-SNOTEL) on meteor burst operation and technology, Doug Kay (US Coast Guard Headquarters) on the Coast Guard VHF system, and LCDR Bob Wenzel (US Coast Guard Office of Research and Development) on Loran-C technology and performance. Finally, LCDR Charlie Pike and Karl Schroeder (US Coast Guard Office of Research and Development) provided overall guidance and help.

APPENDIX A

CHARACTERISTICS OF LAMPS FOR COAST GUARD BUOYS

The characteristics of five types of lamps either used in Coast Guard buoys or of possible applicability for use in Coast Guard buoys have been surveyed. The five types are fluorescent tube lamps, tungsten filament lamps, xenon flash tubes, light emitting diodes, and high intensity discharge lamps.

FLUORESCENT TUBE LAMPS

Fluorescent tube lamps are probably the most efficient with respect to luminous output for electrical power input. They radiate effectively almost over the entire visual spectrum with a luminous efficacy of about 80 lumens/watt, which is about 10 times that of tungsten incandescent lamps. Normal life time can be measured in many thousands of hours as ordinarily used. Efficiency of fluorescent lamps depends upon the type of phosphor used, with the most efficient being called "white" or "warm white." Of the electrical energy delivered to the lamp, 60% is converted to radiation at 2537Å. Conversion of this radiation to the visible spectrum is accomplished by the phosphor coating with an efficiency of about 45%. Heat energy leaving the lamp is usually less than 25% of that from an incandescent tungsten lamp. Phosphor imperfections and output degradation in the first 100 hours of life reduce the output to 60-65 lumens/watt. Color can be adjusted to some extent by choice of phosphor. The spectral distribution is relatively constant throughout life. The average luminance of a fluorescent tube lamp is expressed as:

$$\frac{\text{Lamp lumens}}{9.25 \times \text{lamp diameter (cm)} \times \text{length (cm)}}$$

A fluorescent tube can be coated with a reflective layer of aluminum between the glass and phosphor. Emission through the aperture segment without a reflective coating would carry a six fold increase of luminous output per cm^2. The aluminum reflective coating could be applied also to the outside of the glass. A fluorescent ring lamp with such a coating applied can be used to increase the light output through the Fresnel lens of a buoy.

Lamp brightness values are determined in candles/in^2. For example, a 12 in diameter, 32 watt, ring tube lamp has a brightness of 5 candles/in^2 or approximately 0.8 candles/cm^2. The average luminance (candles/cm^2) =

$$\frac{\text{Lamp lumens}}{9.25 \times \text{ring diameter} \times \text{tube cross-section}}$$

$$0.8 \text{ candles/cm}^2 = \frac{\text{Lamp lumens}}{9.25 \times 94 \text{ cm} \times 2.54 \text{ cm}}$$

Lamp lumens = 1707 for this 32 watt lamp. This is equivalent to 55 lumens/watt. With a reflective coating on the ring, this 55 lumens/watt could be increased over 3 or 4 times, to yield about 200 lumens/watt.

If such a lamp buoy could have long periods of "on" time, the life time of the fluorescent tube could be measured in many thousands of hours. However, if such a lamp were to be used as a flasher, its lifetime would be severely shortened to the point of impracticality. In addition, fluorescent type lamps are subject to temperature conditions affecting luminous output. Therefore, it would appear that fluorescent lamps, unless used in warmer climates and with long "on" times (hours), and a mechanical shutter of some sort, may not be as an attractive a choice as would be at first considered.

TUNGSTEN FILAMENT LAMPS

The tungsten filament lamp presently used in Coast Guard buoys consists of an S-8 or S-11 bulb with a C-8 filament. Figure A-1 is a graph showing luminous output flux with respect to filament current. The voltage in all cases remains at 12.0 volts; only the filament cross sectional area differs according to current for 500 hour life. Considering rated life, duty cycle, and luminous output flux, the presently used bulbs are probably the best of the tungsten types. The luminous efficacy (lumens/ watt) is of the order of 8 or less. Bulbs with higher outputs appear to have much shorter lives because of tungsten filament evaporation rates.

A tungsten C-8 filament, 12 volt bulb requiring 32 watts input power would emit about 520 lumens or 16 lumens/watt. An S-11 bulb with 600 lumen output (12 V @ 3.05 A) at 37 watts should also emit 16 lumens/watt. A 16% duty cycle for a flashing tungsten type bulb would consume about 6 watts (16% x 37). It would therefore appear that a flashing S-11 tungsten bulb is still more efficient than a continuously burning comparable fluorescent bulb.

XENON FLASH TUBES

The characteristics of representative xenon flash tubes are shown in Table A-1. These tubes appear to offer at least some advantages as light sources for buoy use. Power requirements appear to be within the limits for solar voltaic charge sources. The Coast Guard does use xenon type flash units for some buoy applications at the present time. Generally, a major problem with xenon electronic flash type equipment is the saturation effect on the rods and cones in the eye retina. The

12 VOLTS INPUT AND WITH C-8 FILAMENTS OF VARIOUS CURRENT CAPACITIES – ALL AT 500 HOUR RATED LIFE

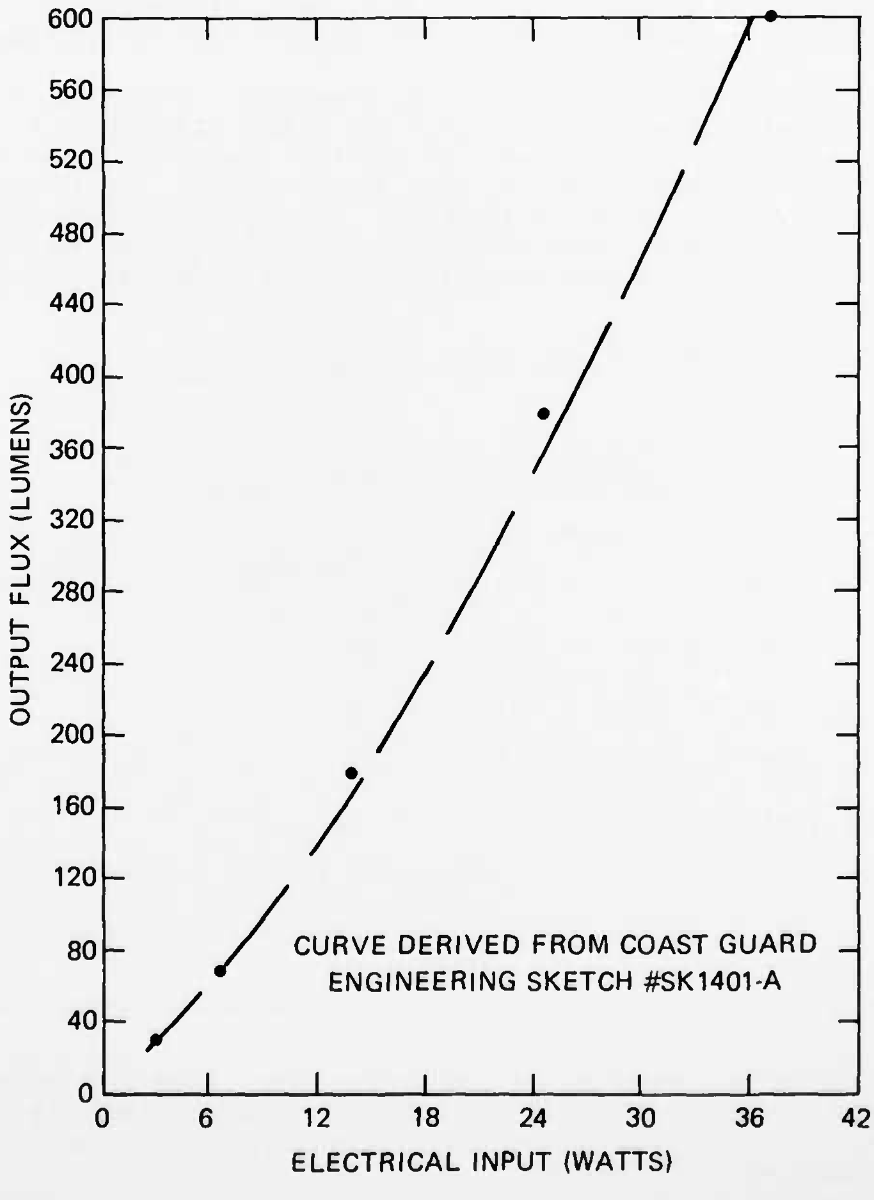


FIGURE A-1 LUMINOUS OUTPUT FOR TUNGSTEN FILAMENTS.

light bursts are usually so intense that, although short, eye saturation prevents an accurate estimate of light source size and relative placement. This can make relative distance estimations completely inaccurate. However, some xenon flash tubes can be pulsed at speeds and light levels which help avoid the sense of flicker and allow the iris of the eye to accommodate to the light level. This type of xenon bulb is of relatively low enough power to avoid serious heating.

For flickerless lighting consider a repetitive flash rate of 60 per sec with an individual flash duration of 1.2 microseconds. The peak intensity at this rate would be approximately 5×10^6 candles measured at 1 meter and at the center of a $\pm 10^\circ$ beam (to ½ power points). The color temperature would be about 6500°K. The capacitor of this strobe at this repetition rate should be 0.255 microfarads with a charge voltage of 800 volts.

$$1/2\ (CV^2) = .0816 \text{ watt seconds energy input}$$

TABLE A-1 - CHARACTERISTICS OF REPRESENTATIVE XENON FLASH LAMPS

Flash Rate (per sec)	Peak Intensity (candles x 10^6)	Duration (microseconds)
1.8 - 11.5	15	3
11.2 - 70	5	1.2
67 - 417	1	0.8
400 - 2500	.16	0.5
	Measured at 1 meter at $\pm 10^\circ$ to half power points.	Measured at one-third of peak intensity.

The beaming, because of the reflector, is $\pm 10^\circ$ to the half power points. This is equivalent to approximately 0.124 square meters, which is approximately 1/100 of a full 4 π steradians. Therefore

$$\frac{5 \times 10^6 \text{ candles}}{100}$$

would provide a peak power radiated into 4 π steradians of 50,000 candles/flash.

$$\frac{.0816 \text{ watt sec}}{1.2 \times 10^{-6} \text{ sec (the duration)}} = 68{,}000 \text{ watts equivalent peak power}$$

$$\frac{50{,}000 \text{ lumens (in 1 steradian)}}{68{,}000 \text{ watts}} = 0.735 \text{ lumens/watt efficiency}$$

The xenon flashtube appears to be one of the more promising lamps surveyed and should be examined with a view toward modifying and using it to meet Coast Guard requirements.

LIGHT EMITTING DIODES

High-efficiency light emitting diodes (LEDs), which can operate in the yellow, red, or even green portions of the spectrum, have been surveyed. With the yellow type, axial luminous intensity at 25°C is about 4 millicandles with a 10 mA current and a voltage of 2.2 volts. This represents a power consumption of .022 watts. If these LEDs were to be stacked and arranged around a cylinder, and with an assumed 50 watt total budget, a total of 50/.022 = 2268 individual LEDs would be used with a combined output of .004 x 2268 = 9 candles. Roughly one fifth of these are radiating in any one steradian direction. Therefore, at best, 2 lumens divided by 50 watts, or .04 lumens/watt is the efficiency. This efficiency is not sufficient for buoy use.

HIGH INTENSITY DISCHARGE LAMPS

High intensity discharge lamps require starting currents sufficient to vaporize metals or compounds contained in a small arc tube which is in turn placed within a larger heat conserving envelope. Generally there are three types: mercury, metal halide (including mercury and metal iodides), and high pressure sodium. Although the light output is very high, the power required to start an arc and maintain it is also very high. In addition a long time period is required for starting--measured in minutes in most cases. Spectrally these sources range from blue or blue green to yellow. Color can be shifted to some degree by means of phosphor coating on the bulb. Lifetimes can be measured in thousands of hours if the lamps are operated for several hours per start. For small solar voltaic charged power supplies, these high pressure arc lights do not appear useful.

Table A-2 summarizes the relative efficiencies of these light sources. Table A-3 summarizes the relative brightness of various sources.

TABLE A-2 - EFFICIENCY SUMMARY

Fluorescent Tube Lamps	∿ 80 lumens/watt
Tungsten Filament Lamps	∿ 16 lumens/watt
Xenon Flash Lamps	∿ 0.75 lumens/watt at 60 cps rate
Light Emitting Diodes	∿ 0.04 lumens/watt
High Intensity Discharge Lamps	>> 50 lumens/watt

TABLE A-3 - RELATIVE BRIGHTNESS OF VARIOUS SOURCES

Source	Brightness (candles/cm^2)
Night Sky	5×10^{-9}
Mercury Arc (high pressure)	5×10^{-5}
Carbon Arc	10^4 to 10^5
Tungsten $3655^{\circ}K$	5.7×10^3
Tungsten $3500^{\circ}K$	4.2×10^3
Tungsten $3000^{\circ}K$	1.3×10^3
Tungsten Filament (ordinary lamp)	5×10^2
Tungsten Filament (projector lamp)	3×10^3
Fluorescent Lamp	0.60
Least Perceptible Brightness	5×10^{-11}
Least Perceptible Point Source	2×10^{-8} (at 3 meter distance)

60 BCPS (Beam Candle Power Seconds) appears brighter than a third magnitude star at a 20 mile distance.

APPENDIX B

ANP POWER AND POWER SYSTEM MANAGEMENT

GENERAL

The power system for the ANP can be automated with microprocessor technology not only to provide for essential battery charge control, but to perform a variety of system level performance checks which can prove highly beneficial to Coast Guard maintenance personnel. The purpose of this appendix is twofold: (1) to indicate the extent to which energy is available to support operation of the ANP, and (2) to suggest a useful power system control and diagnostic program which could be implemented by the onboard microprocessor.

AVAILABLE POWER

Since the photovoltaic solar panel is one of the more costly elements of the system, it will be assumed that buoy panels will be mounted horizontally for maximum collection efficiency. Since the area available for mounting is not unlimited, a panel producing an electrical power output of 70 watts at 100 mW/cm^2 illumination intensity will be assumed to be the maximum size available. This appears consistent with Coast Guard information provided in Figure B-1 which illustrates the mounting of various sizes of panels in the buoy ring directly above the lantern.

The energy available to support lantern operation and the other onboard equipment will be a function of panel size, the latitude at which the buoy is deployed, and the locally available solar insolation. A method for calculating the theoretical "clear sky" solar insolation at any sea level location is outlined in SR-81-3*. A summary of the results of this analysis is provided in Figure B-2. Utilizing this method and comparing the results to measured data at several U.S. coastal sites indicates that insolation ranging from approximately 70% to 115% of theoretical may be realized. Values in excess of 100% of theoretical are attributable to sky radiation, reflections from clouds, etc. Table B-1 illustrates the theoretical versus measured twelve year average solar insolation for Seattle, Washington. The ratio of measured to average monthly insolation may be observed to vary from a minimum of 70% to a maximum of 94%. In order to make conservative estimates of the load sustaining capability of the solar panels and to estimate the required battery capacity to operate these aids, an available solar insolation which is 70% of theoretical will be assumed.

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*Allen, W.E., "U.S. Coast Guard Study on Solar Powered Aids to Navigation," JHU/APL, SR-81-3, February 1981.

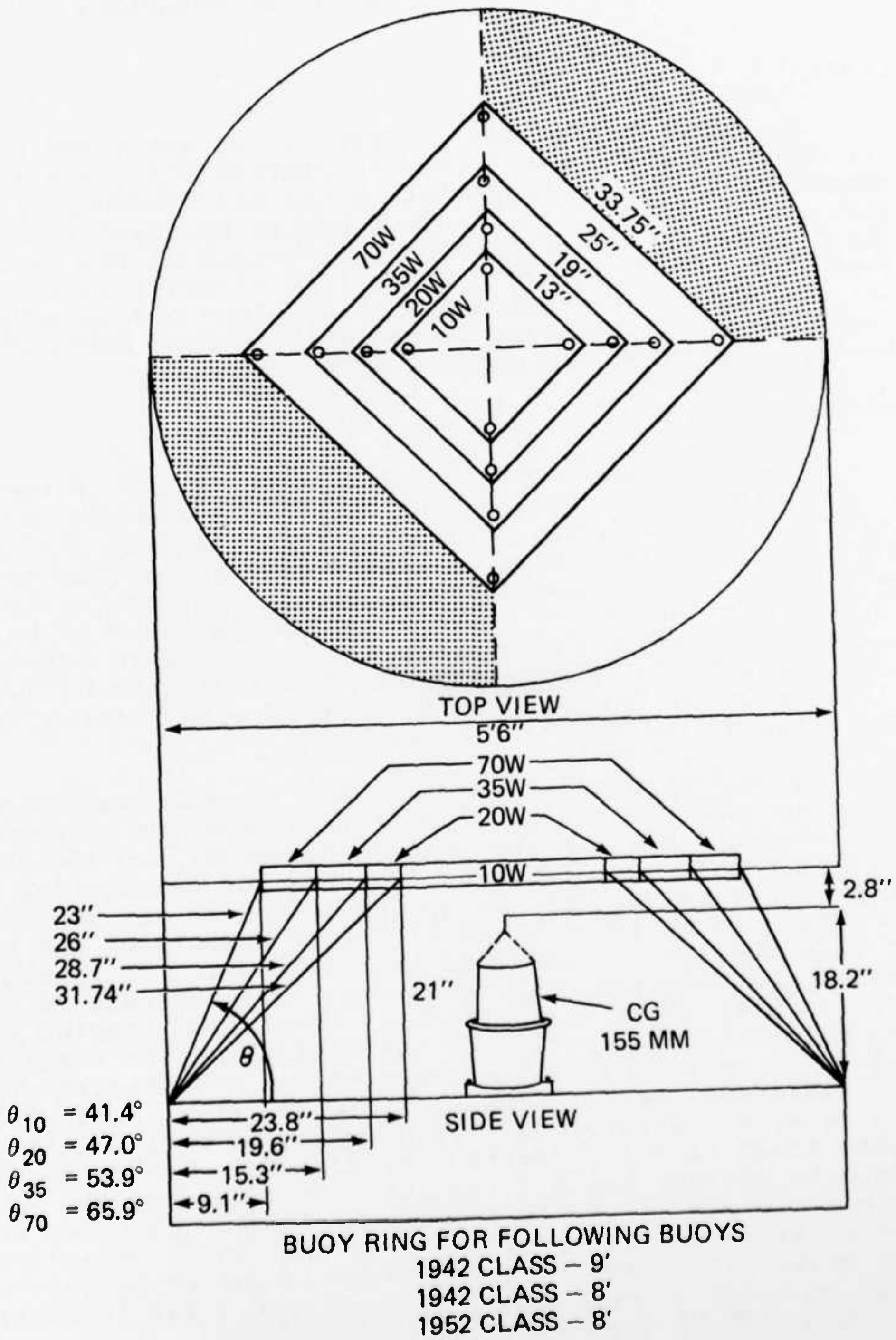


FIGURE B-1 SOLAR PANEL MOUNTING IN BUOY RING.

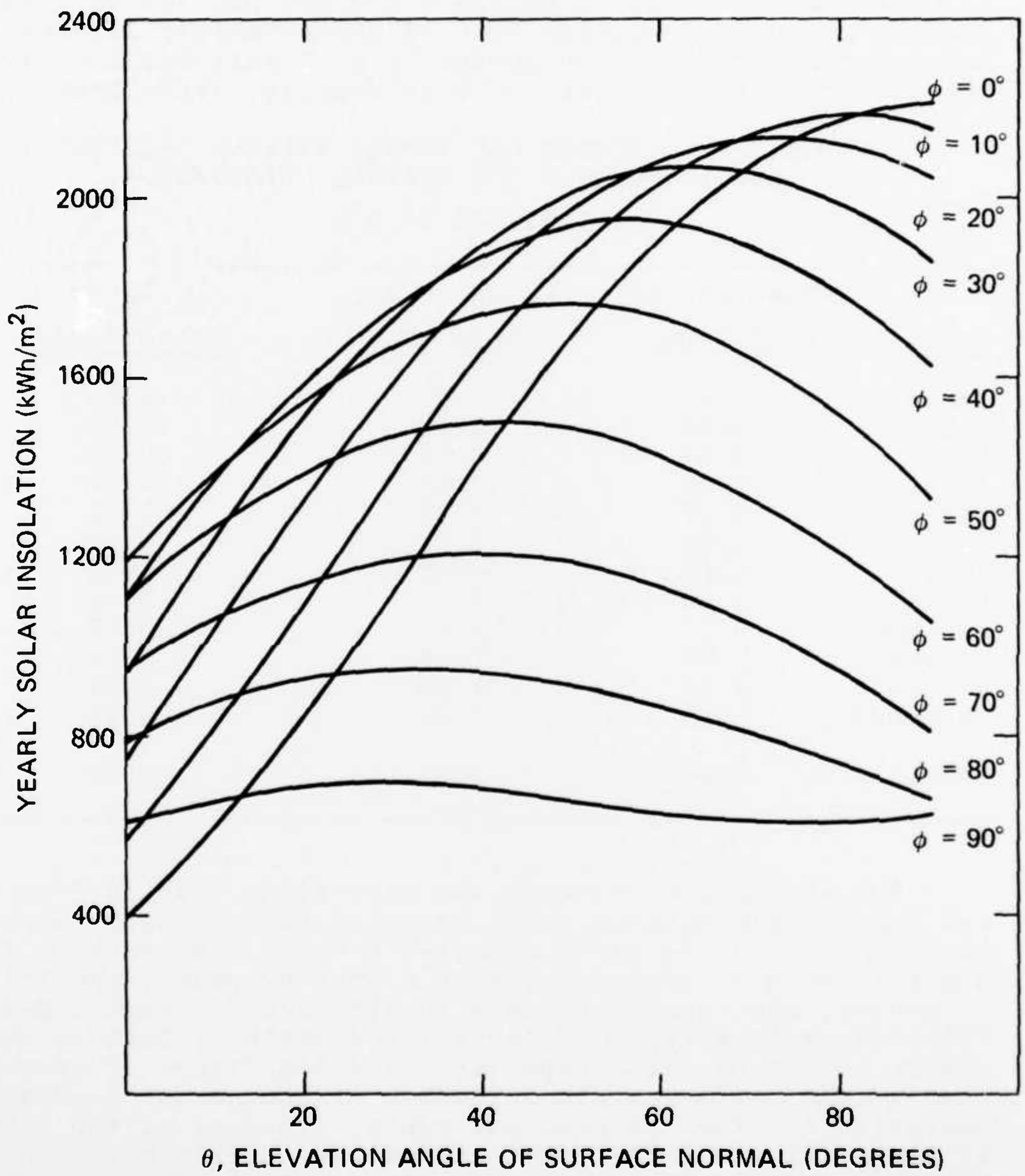


FIGURE B-2 THEORETICAL YEARLY CLEAR SKY SOLAR INSOLATION ON A SOUTH FACING PANEL AS A FUNCTION OF LATITUDE ϕ AND ELEVATION ANGLE θ OF THE PANEL NORMAL ABOVE THE HORIZON.

Figure B-3 summarizes the maximum supportable electrical load aboard the aid as a function of solar panel size and latitude for 70% of "clear sky" solar insolation. This load is expressed in terms of ampere-hours per day for an assumed 12 volt system. A maximum load of approximately 16 ampere-hours per day could be supported by a 70 watt horizontal panel at locations as far north as Seattle, Washington.

TABLE B-1 - THEORETICAL VERSUS AVERAGE MEASURED SOLAR INSOLATION FOR SEATTLE, WASHINGTON, LATITUDE 47.5°N

Month	Theoretical kWh/m^2-Day	Measured Avg. kWh/m^2-Day	Ratio Meas/Theor.
January	1.11	0.93	0.84
February	1.98	1.63	0.82
March	3.47	2.79	0.80
April	5.14	4.07	0.79
May	6.47	5.23	0.81
June	7.09	5.52	0.78
July	6.87	6.10	0.89
August	5.86	5.52	0.94
September	4.29	3.72	0.87
October	2.65	1.86	0.70
November	1.44	1.16	0.81
December	0.91	0.76	0.84
YEARLY AVG.	3.94	3.33	0.85

For any system in which the electrical load is less than the supportable maximum, some tradeoff between array size and battery size can be made; a larger battery can be used, for a given depth of discharge, with a smaller panel, providing, of course, that energy balance is attainable. Figure B-4 illustrates this tradeoff for a fixed depth of battery discharge to 50% of rated capacity. The 50% figure is generally used as the maximum depth allowable discharge for lead-acid batteries in order to preclude winter freezing of the electrolyte (see Figure B-5). The maximum permissible battery capacity for use in an aid will ultimately be determined by available space and/or, in the case of a buoy, the allowable loss of freeboard. In any event, the energy utilized by onboard equipment should be kept at a minimum in order to minimize the size, hence cost, of the energy generation and storage system.

BATTERY CHARGE CONTROL

Battery charge control in an advanced aid to navigation must be readily adaptable to meet the evolutionary changes in battery types which are certain to occur. A microprocessor

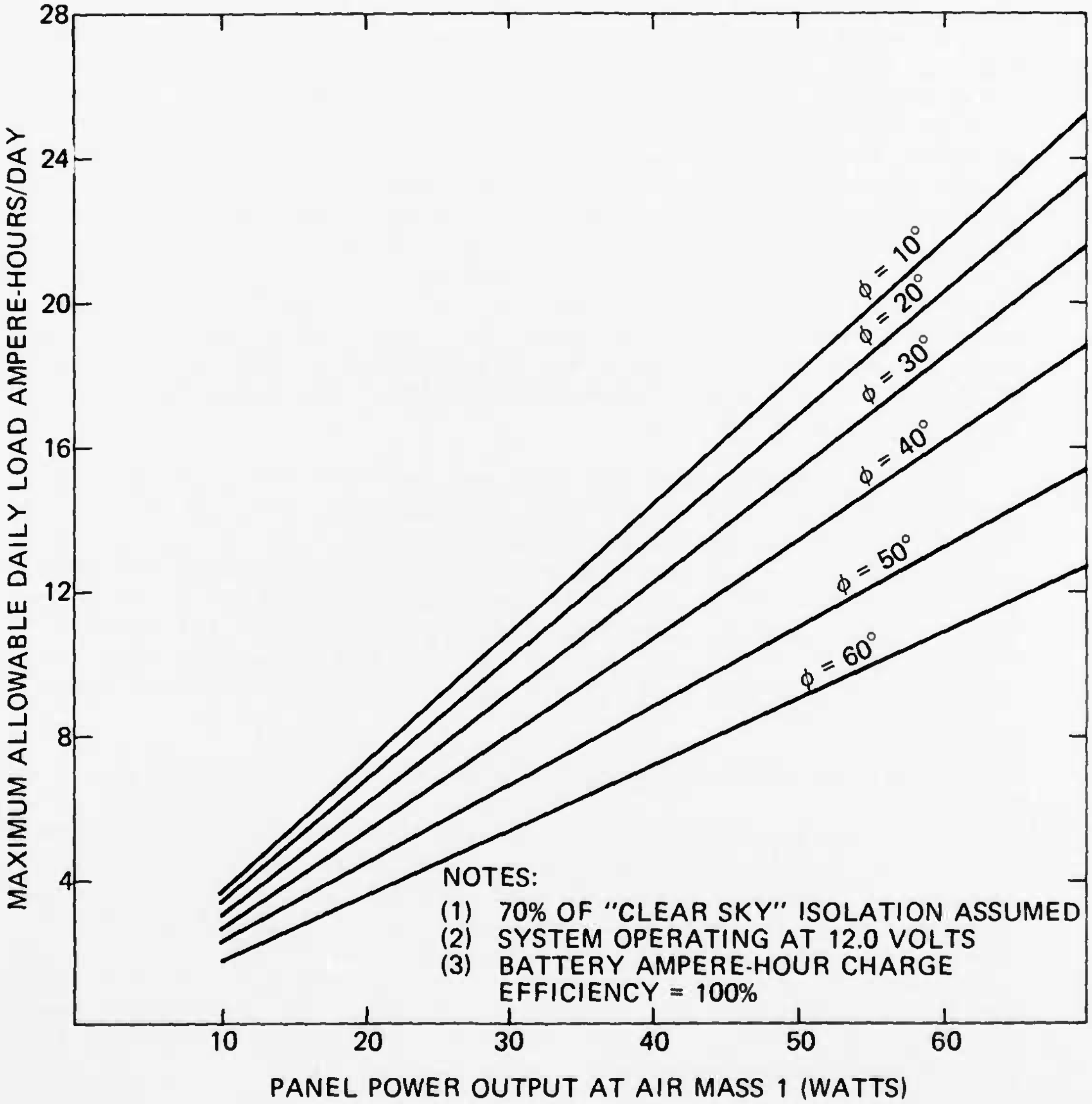


FIGURE B-3 PERMISSIBLE SOLAR POWER SYSTEM ELECTRICAL LOAD AS A FUNCTION OF SOLAR PANEL POWER OUTPUT AND LATITUDE FOR A SYSTEM WITH A HORIZONTAL PANEL.

based charge controller is well suited to this task. Figure B-6 illustrates the proposed battery charge control concept utilizing a microprocessor. Based on experience with linear shunt regulators (see SR-81-3*) it is felt that an even simpler ripple shunt regulator could be used as the control element. Such a regulator will selectively short the solar array, thus reducing the average charge current. Control of battery overcharge is exercised by limiting battery voltage to some safe maximum commensurate with temperature. A typical voltage limit transfer function is illustrated in Figure B-6. The microprocessor would maintain closed loop control over battery input current by sensing battery voltage and comparing it with a limit voltage calculated internally as a function of battery temperature as shown in Figure B-6. If battery voltage is below the maximum allowable, the shunt is disabled so that maximum current is received by the battery. The slope and intercept of the voltage-temperature curve are presumed programmable and are stored in RAM.

The microprocessor based system should also be capable of disabling selected loads, should battery voltage (or state of charge) fall below some preset minimum. By so doing, the battery will be protected from damage, and maintenance personnel will be advised of either a system overload or a solar panel deficiency by some resultant aid performance deficiency. A suggested program logic to perform this function and to implement regulator control of battery overcharge is provided in a following section.

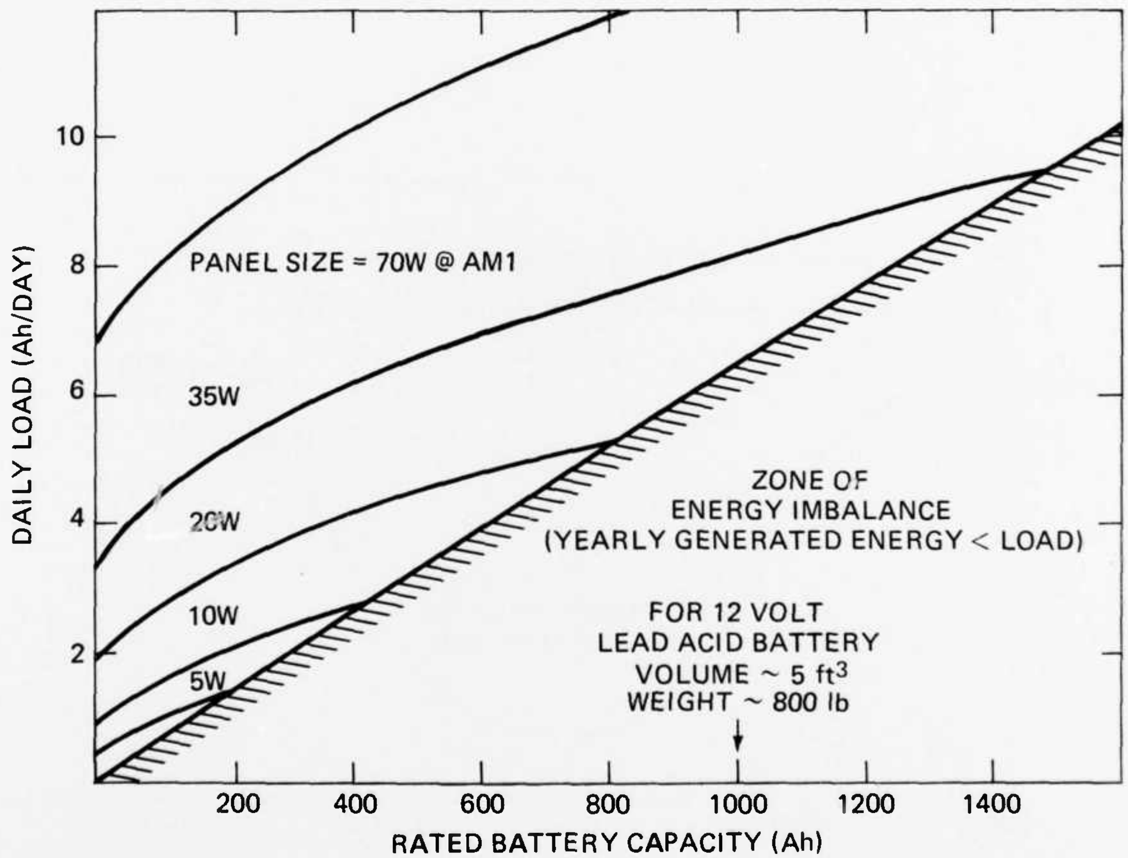
POWER SYSTEM INTERNAL CHECKS AND TRANSMITTED DATA

The aids will routinely, and when interrogated, transmit selected status information to shore via RF link. The microprocessor based system can and should perform internal power system functional checks identifying, if possible, faults in the system and alerting maintenance personnel in sufficient time to take remedial action before an outage occurs. Although the possibilities are almost limitless, as a minimum requirement the following status flags or telltales could be transmitted on a routine basis:

1. Zero lamp current
2. Low battery voltage
3. Battery discharge current excessive
4. Low battery capacity
5. Zero solar current

Flags, when set, should indicate an anomaly has occurred within the 24 hour period immediately preceding data transmission. They should be reset or cleared after data have been

*Allen, W.E., "U.S. Coast Guard Study on Solar Powered Aids to Navigation," JHU/APL SR-81-3, February 1981.



NOTES

(1) HORIZONTAL PANEL
(2) 70% OF "CLEAR SKY" INSOLATION ASSUMED
(3) AMPERE HOUR EFFICIENCY OF 100% ASSUMED
(4) 12 VOLT SYSTEM

FIGURE B-4 DAILY LOAD AND SOLAR PANEL SIZE VS RATED BATTERY CAPACITY FOR 50% DEPTH OF BATTERY DISCHARGE AT 40°N LATITUDE.

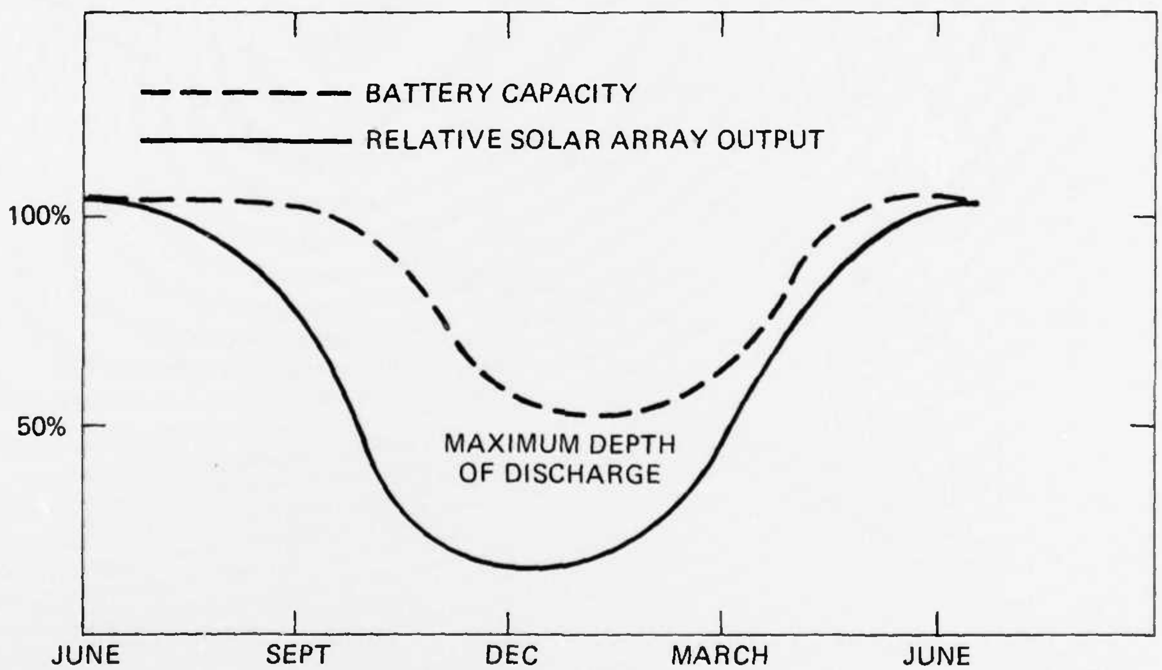


FIGURE B-5 TYPICAL SEASONAL BATTERY DISCHARGE

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FEASIBILITY STUDY FOR AN ADVANCED LIGHTED AID TO NAVIGATION.(U)
SEP 81 S JASKULEK, E J HOFFMAN, W E ALLEN N00024-81-C-5301
UNCLASSIFIED USCG-D-48-81 NL

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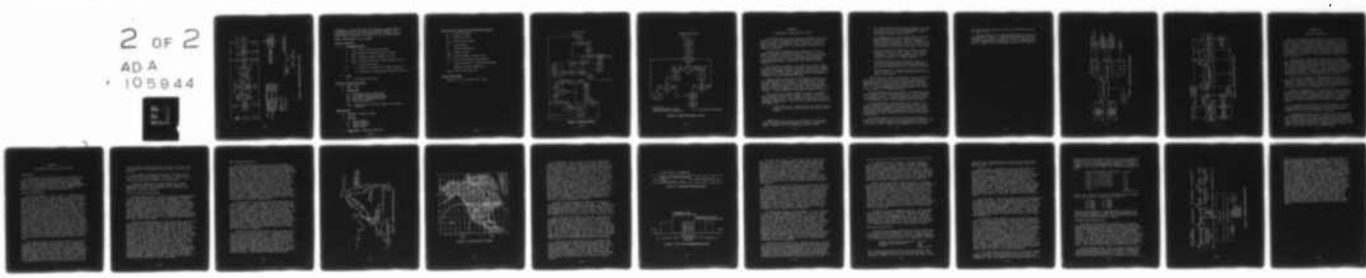

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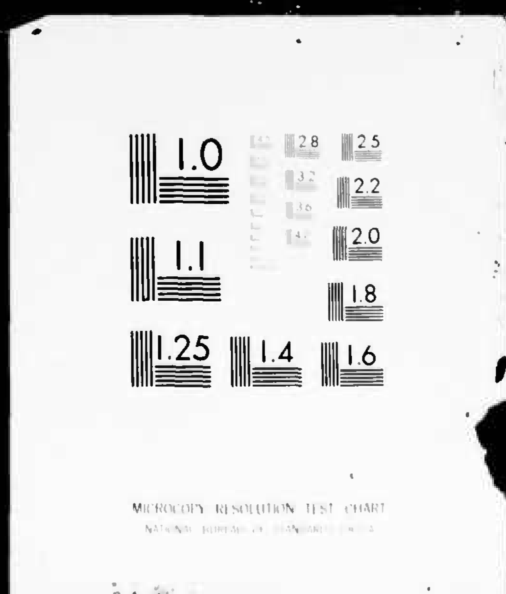


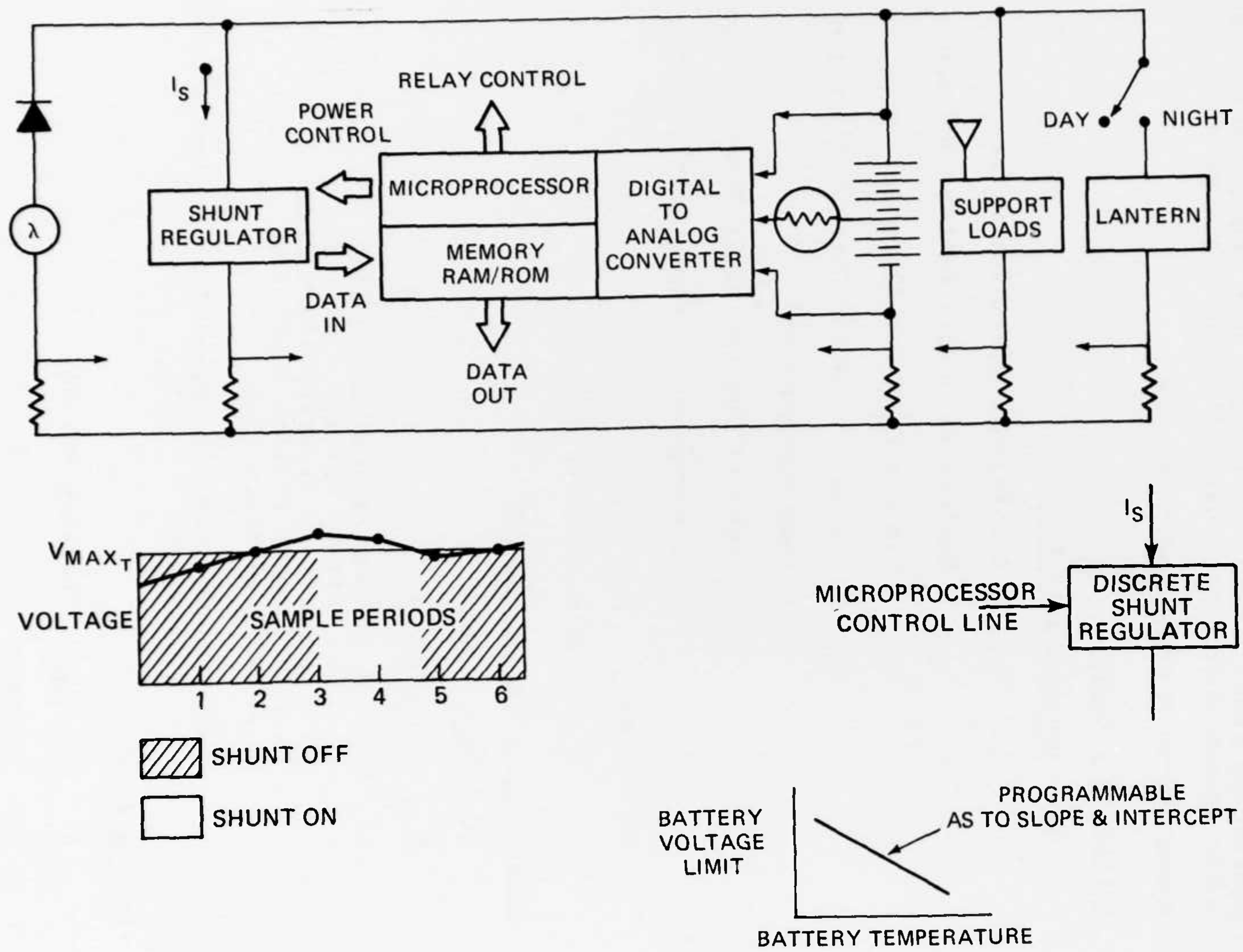


FIGURE B-6 PROPOSED CHARGE CONTROL CONCEPT.

transmitted. Recurring flags will therefore clearly suggest a malfunction in one or more of the system elements. No particular benefit is to be derived from the transmission of power system performance data other than on a go-no go basis.

POWER SYSTEM CONTROL LOGIC PROGRAM

Inputs to Program

A. Programmable Data

1. V_{Low} = Low Voltage Alarm Set Point.

2. V_{Min} = Minimum Allowable Battery Voltage.

3. C_{Min} = Minimum Capacity Alarm Set Point.

4. I_{Max} = Maximum Discharge Current Alarm Set Point.

5. P = Lamp Flash Period.

6. m = Slope of Voltage Limit Transfer Function.

7. b = Intercept of Voltage Limit Transfer Function.

B. Flag

F_o = Integrator Reset Flag

Outputs to Telemetry System

A. Data - None

B. Alarm Flags

F1 - Zero lamp current alarm flag
F2 - Low battery voltage alarm flag
F3 - Low battery capacity alarm flag
F4 - Zero solar current alarm flag
F5 - Overload alarm flag

Note: Alarm flags are cleared after each transmit sequence.

Sensed Inputs

A. Voltages - Battery Voltage

B. Currents

1. Solar current
2. Battery current
3. Shunt current
4. Lamp current

C. Temperature - Battery Temperature

Definitions of Symbols Used (other than inputs)

V_B = Battery Voltage

I_B = Battery Current

I_{SA} = Solar Array Current

I_L = Lamp Current

T_B = Battery Temperature

I_{SH} = Shunt Current

+AH = Battery Charge, Ampere-hours

-AH = Battery Discharge, Ampere-hours

t = Time from Start of Lamp Flash Sequence

C = Battery Capacity Remaining

V_{lim} = Battery Voltage Limit

Program Flow Chart

Figure B-7 is the program flow chart.

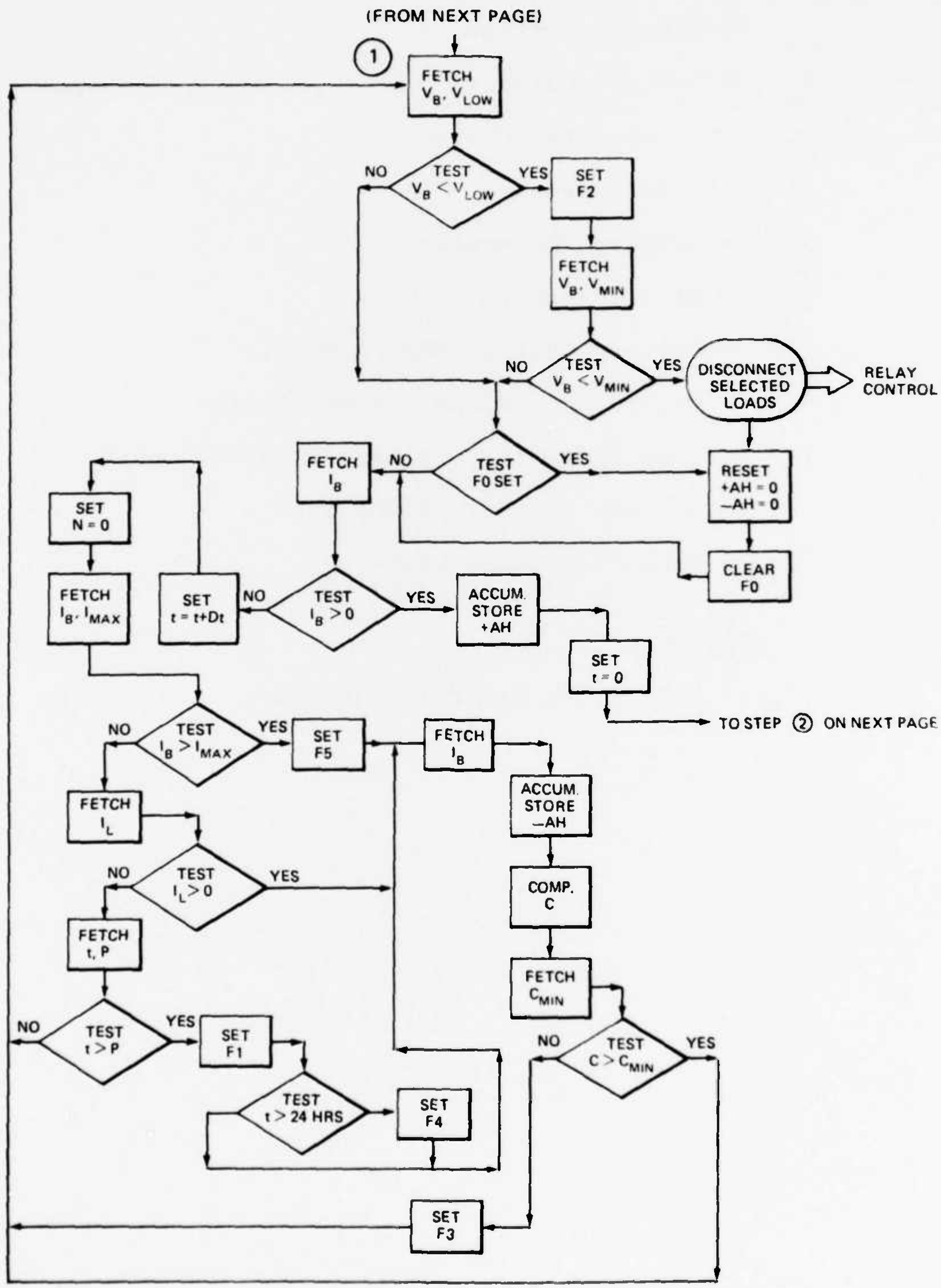
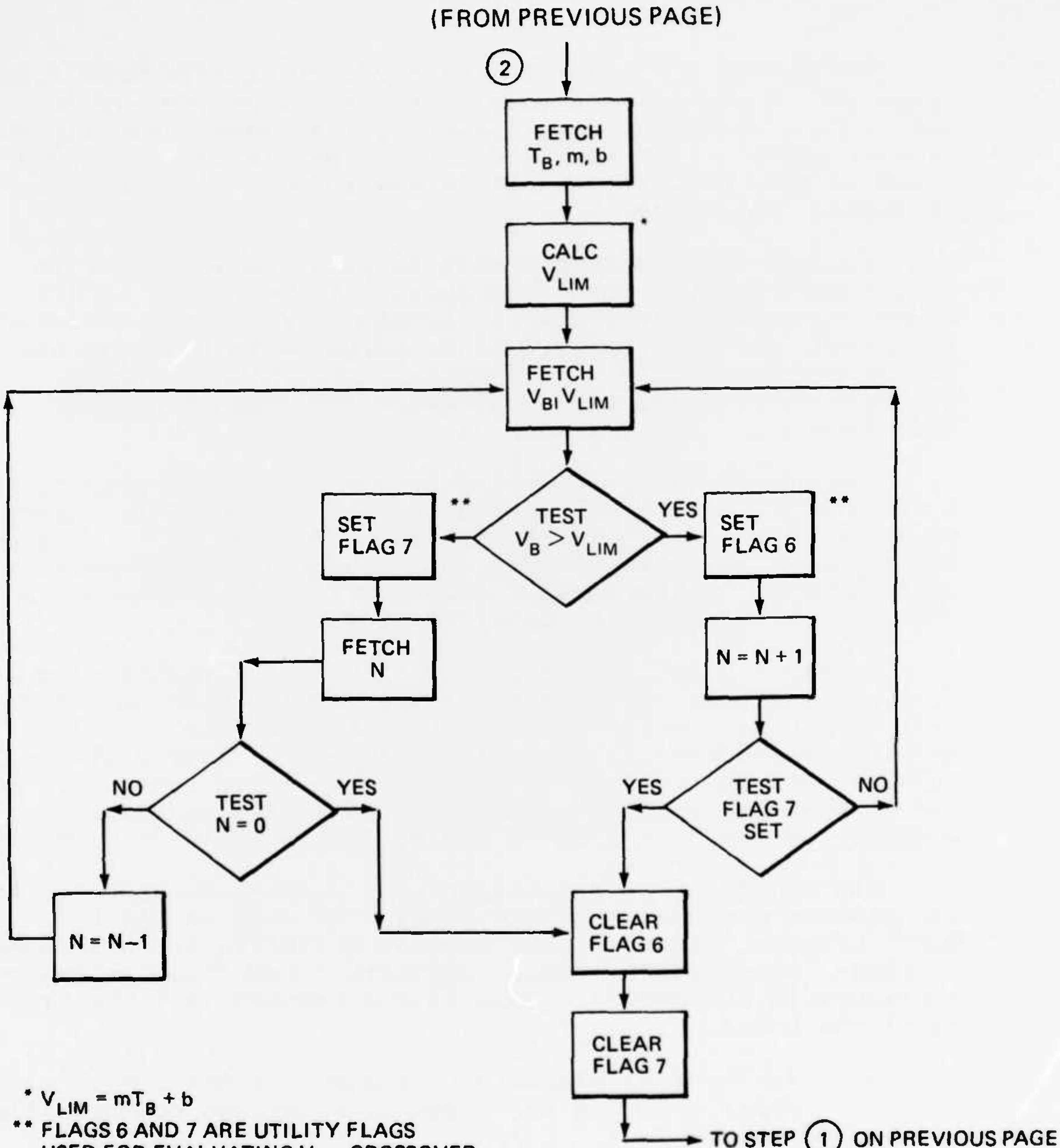


FIGURE B-7 PROPOSED PROGRAM.



* $V_{LIM} = mT_B + b$

** FLAGS 6 AND 7 ARE UTILITY FLAGS USED FOR EVALUATING V_{LM} CROSSOVER

FIGURE B-7 PROPOSED PROGRAM (2 PAGES)

APPENDIX C

ELECTRONICS PACKAGE DESIGN DETAILS

The design goals for the electronics package were driven primarily by the environmental constraints on the system; it had to be a small, rugged, low-cost, low-power, intelligent, modular system. The detailed circuit design is beyond the scope of this project, but it is possible to block out the necessary components.

Because these packages will be situated in a hostile marine environment, the electronics will be put in an air-tight, resealable water proof canister. After the enclosure is sealed, the air inside will be purged with nitrogen gas via an external valve. This process should help remove moisture surrounding the electronics and improve package reliability.

The electronic circuitry in an ANP can be divided into four subsystems; the process controller, transmitter, command receiver, and Loran-C receiver. Each of these will be incorporated on a separate circuit board for easy maintenance and configuration*. The Loran-C module will only be installed on a buoy or a fixed loran signal monitor.

Figure 4 shows the four main electronics modules for a full navigational aid platform. The modules will interface with each other over a backplane. The backplane ties into external connectors which link the antennas, lamp assembly, battery, and solar array to the system. These connectors are the sole means of interfacing with the sealed electronics package. A block diagram of the system is shown in Figure 5.

The operation of the electronics package is directed by the process controller module (PCM). As seen in the PCM Block Diagram, Figure 6, the control circuitry for all communications, diagnostics, power regulation, and flash activity is contained in the module. Some of its features will be briefly mentioned below.

1. An internal clock is maintained on the PCM to assure correct timing for light flashing and communications windows.

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*Note that the transmitter and command receiver may be combined into a transceiver module or simply a transmitter module, depending on the communications link chosen.

2. The flash pattern type and relationship to the rest of an ANP flash chain are stored in RAM on the PCM. Also stored in RAM is the communications window assignment for that particular ANP.

3. All communications to and from the ANP are enabled and processed by the PCM. Transmission data is coded with error detection bits and appended to the ANP ID number before being sent out. Received incoming data are checked to verify that the destination ID and error detection information are correct.

4. The ANP's status is monitored by means of sensors placed on and off the PCM. Data, such as battery temperature, voltage, and incident solar energy, are used to control the charge regulator and determine the health of the ANP's systems.

5. The PCM turns the Loran-C receiver on and off, assists in proper lock-up procedures, and stores the time difference (TD) data for transmission. No processing is performed on the TD data in the PCM.

6. The PCM generates a message stream consisting of ANP ID, position, and status information for transmission to the MCS.

A block diagram of the microcomputer is shown in Figure C-1. This part of the PCM will be running continuously; therefore, it must have a low power drain and be reliable. CMOS technology is well-suited for applications like this, and there is an increasingly wide range of components made with it. The microcomputer's active components will therefore be made with the CMOS fabrication.

The microprocessor will not need much computing or high speed capability for this application, so a 4-bit processor will probably suffice. An 8-bit processor would cost only a few dollars more, and would add more system flexibility in the development stages. Either choice would do the job.

The microprocessor was given 4K bytes of ROM and 128 bytes of RAM to store program instructions and data. The analog diagnostic sensors will be connected to the microcomputer via a multiplexed 6-bit analog to digital converter. An interface to the Loran-C receiver may be a USART or some other buffer circuit, depending on the receiver's interface capabilities.

The system clock is used to synchronize the flashing sequence of the ANP's light, as well as time the communications. If the final system design allows resynchronizing the clock only once per day, a temperature compensated or controlled

oscillator may be required to maintain the desired accuracy of 1 part in 10^7.

The microcomputer will draw approximately a continuous 3 mA current at 5 volts. A small 5-volt regulator will be included on the PCM to provide this voltage. The oscillator will draw approximately 10 mA more if it is temperature contolled. Figure C-2 is the ANP power system block diagram.

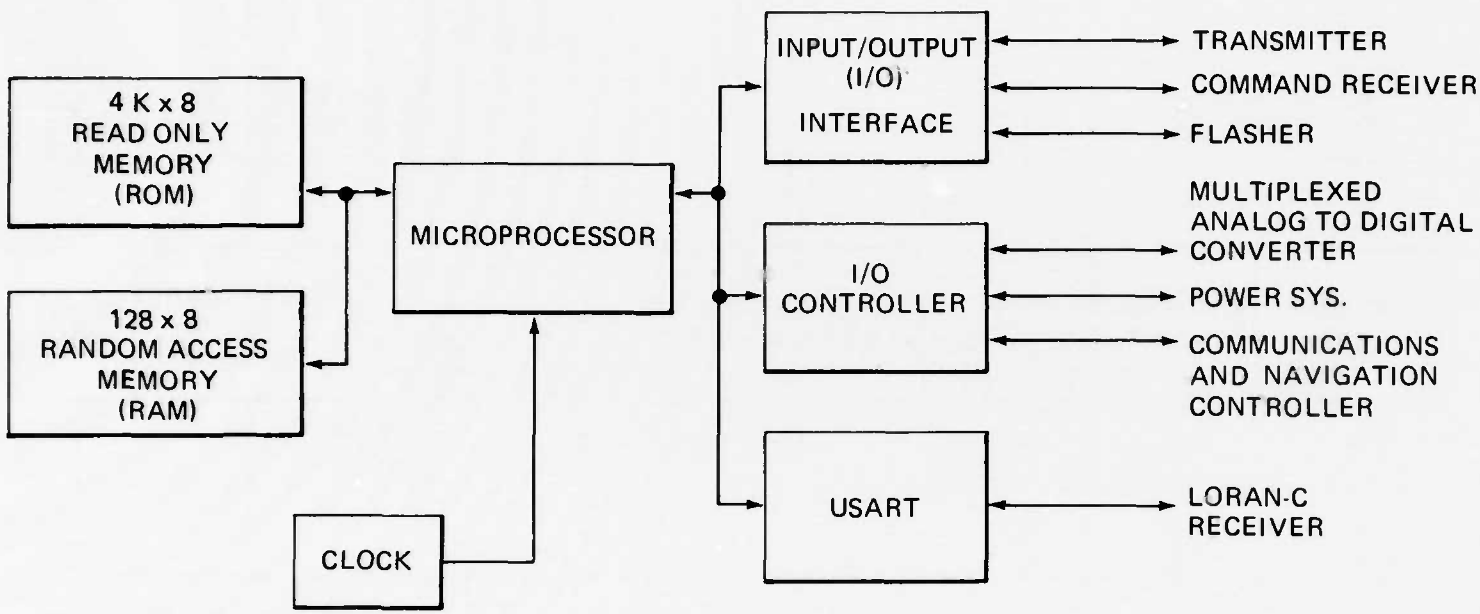

FIGURE C-1 MICROCOMPUTER BLOCK DIAGRAM.

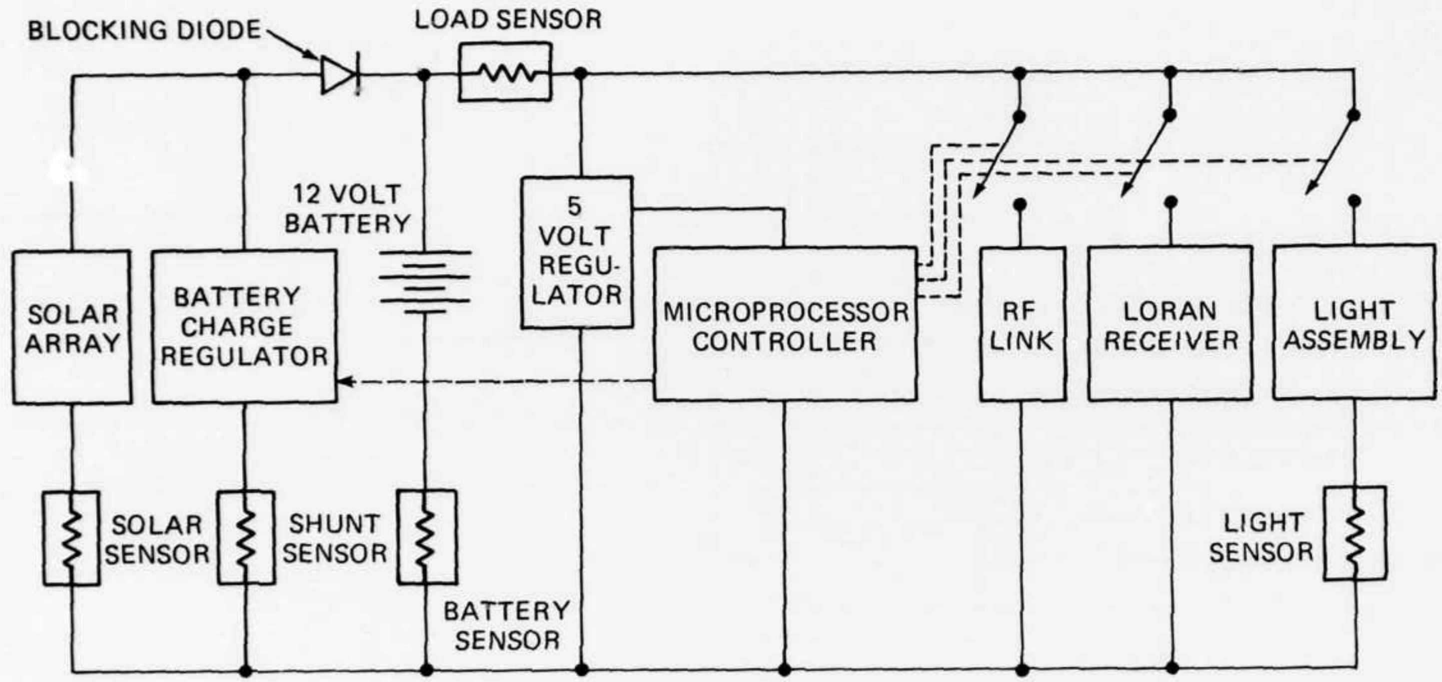

FIGURE C-2 ANP POWER SYSTEM BLOCK DIAGRAM.

APPENDIX D

LORAN-C POSITIONING

One of the major design goals for the AAN Network is a capability for remotely determining the position of moored ANPs. The most likely source of such information is the Coast Guard Loran-C navigation system. The Loran-C transmissions, broadcast from shore stations, will be picked up by a Loran-C receiver on the buoys. This receiver is similar to most commercial, automatic Loran-C receivers, except that it is capable of 10 nsec TD resolution and can be remotely operated by a microcontroller. The normal panel displays will not be needed.

To save power, the Loran-C receiver will be turned on, under microcomputer control, for only about 30 minutes per day. Receiver lockup and signal resolution will be aided by the various software algorithms stored in ROM via the Loran-C receiver-microcomputer interface. The receiver will be capable of tracking the master and two or three secondary stations in a given operating area (depending upon local Loran-C geometry and signal strength). The derived TDs will be sent to the microcomputer and then the receiver will be turned off.

The accuracy required for determining the location of a buoy is not clearly defined. A buoy's watch circle radius is generally quoted at 2-3 times the depth of the water at that location, leading to a design goal of about 30 meters accuracy. This kind of accuracy is obtainable with Loran-C equipment, assuming certain factors are taken into account.

Loran-C transmissions can be affected by various factors along their propagation paths. These factors, such as unusual weather fronts, coastline interfaces, and ratio of distances over land to water, can change the timing of the signals on both a systematic and a daily basis and introduce errors. A couple of corrective measures will be used to reduce these errors.

To overcome the systematic errors introduced by the non-ideal propagation path to any buoy, each buoy site will be surveyed at the time of deployment. The TD information recorded will be the "home" position of the buoy.

Overcoming the random errors introduced by daily changes to the propagation medium will be a little more involved. The best approach here is to make a differential Loran-C measurement, comparing the newly measured TD with some known position. Because the propagation medium is fairly constant over a large area, 50-100 miles, this kind of comparison will eliminate the common error factor, known as the bias values.

The known position measurement will come from Loran-C receivers located on fixed ANPs. Since the receiver's position should be constant, any variations in reported TD's are a measurement of the TD biases in that area.

Calculating whether a buoy is on station using the received TD information can be performed either onboard the buoy or at some shore Coast Guard base station. The first approach requires that bias information be first collected from the fixed Loran-C monitors, processed on shore, then distributed back to the proper buoys. The information could then be used to make a go-no go position determination. This bit of information would then be sent back to the base station.

A simpler approach is to send the uncompensated TDs back to the base station with the other buoy status information. There the data could be combined with TD bias information, and a go-no go decision could be made. This method allows for more flexibility in defining buoy watch circles and monitoring Loran-C transmissions.

By employing this differential Loran-C measurement technique, it should be possible to obtain the desired 30 meters accuracy.*

The Loran-C receiver requires the use of a whip antenna. It may be possible to use this same antenna for the communications link if it is in the VHF band.

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*Wolfson, J.A. et al, "Loran-Based Buoy Position Auditing System Analytical Evaluation," U.S. Coast Guard Research and Development Center, Report No. CG-D-09-80, February 1980.

APPENDIX E

GOES COMMUNICATIONS LINK FOR THE ANP

INTRODUCTION

A design goal for the AAN program is to increase the lifetime and lower the maintenance costs of navigational buoys. The Coast Guard has expressed interest in using solar power, autonomous position locating, and diagnostic reporting to help achieve this goal. This appendix addresses the use of an existing, low-cost satellite communication system to accomplish the communication function.

SYSTEMS CONSIDERATIONS

The first question to ask is whether a communications system is required at all. Conceivably, buoys could be designed having such a high degree of autonomy and reliability that the cost of visiting them infrequently might be less than the communication system cost. Unfortunately, overall buoy "reliability" is also determined by collisions, drifting of buoys off station due to accidentally cut cables, and other external events essentially beyond the control of the designer. Another consideration is the high incidence of buoys erroneously reported out-of-order or off-station. Each of these erroneous reports must be checked out by the Coast Guard. Because of these "external" factors, the required visitation rate would still be too high even if the internal buoy subsystem reliabilities approached 100%. This implies a need for at least one-way communication from buoy to shore station which can indicate with a high degree of confidence that the buoy is on-station and operating properly. A status report received once per day from each buoy would probably suffice, although it might be desirable to have faster access to the small subset of buoys currently reported to be out-of-order. A worst-case longest diagnostic message is estimated to contain only 136 bits plus spares and overhead. There could be as many as 20,000 buoys and other fixed aids nationwide.

The Coast Guard has also indicated a desire to synchronize the flashing lights of arrays of buoys to produce a rippling "airport runway light" effect. This feature would be desired on virtually all of the buoys used in channels, representing about 70% of the total. This requirement implies either an extremely stable, expensive oscillator or two-way communication at least among the buoys themselves. Once we admit to adding a receiver for either timing or synchronization from nearby buoys, it may cost very little more to receive transmissions from the shore or from satellites. So it appears the need for two-way communication may be driven

by the rippling light requirement, but this second link can also be useful in managing the large number of status transmissions.

The required coverage area is taken to be the entire continental U.S. plus offshore waters out to about 25 miles (i.e. out to RF line-of-sight). Coverage of Hawaii and at least the lower half of Alaska is also desirable.

Candidate communication systems considered include direct RF (from VHF down to about 40 MHz), meteor burst, and satellite relay. The remainder of this appendix will address the satellite option.

SATELLITE SYSTEM CONSIDERATIONS

There are three ways to establish satellite communications: build a dedicated satellite, place a "piggyback" transponder on some other satellite already under development, or use channel space on an existing system. The high cost to build and launch dedicated satellites (can easily exceed $50 million each), combined with the low total data requirement (only about 3×10^6 bits/day) argue against dedicated satellites. A dedicated piggyback transponder is a more acceptable option, but first existing available satellite systems must be examined. Existing systems can save not only the spaceborne hardware cost, but also possibly much of the cost of ground reception and data handling. Ground data handling is a frequently underestimated, but non-trivial, cost center.

Satellites communicating to or from buoys have some special constraints. The most important constraint results from the buoy's inability to aim an antenna beam due to pitching and rolling of 30-40° or more. This requires that the buoy antenna have essentially hemispherical coverage, which for practical antennas, yields a gain of 0 dB or even less. The satellite, meanwhile, is required to cover the whole earth (or some large fraction) with its transmitting antenna. The satellite is therefore also beamwidth limited, which is the same as saying it is gain limited. The communication system is therefore of the gain-gain type and so benefits from using the lowest possible frequency. We therefore look for satellites using, say, UHF frequencies to the buoys rather than S, C, or K_u bands. A UHF buoy transmitter will also be less expensive and use less prime power than a comparable microwave unit. In keeping with low cost and simplicity, we also prefer to avoid time-division multiple access in favor of the simpler frequency-division multiple access. Candidate systems in orbit at this time include FLTSATCOM, MARISAT, and GOES. Of these, GOES appears to provide an excellent match to our requirements.

GOES SYSTEM DESCRIPTION

The GOES (Geostationary Operational Environmental Satellite) system is operated by the National Environmental Satellite Service (NESS) of the National Oceanic and Atmospheric Administration (NOAA, part of the Commerce Department). GOES consists of two geosynchronous satellites (at 75°W and 135°W), a Command and Data Acquisition (CDA) station at Wallops Island, and a Central Distribution Facility (CDF) at Suitland, Maryland. GOES is primarily an imaging weather satellite system, but as a secondary mission a Satellite Data Collection System (DCS) is provided to relay brief environmental data messages from sensor platforms throughout the western hemisphere. Participation in the DCS is by Memorandum of Agreement with NESS, and the satellite and ground data services are provided at no charge. However, to qualify for participation, the data must be of an "environmental" nature. Informal discussions with NESS indicate it would probably be acceptable if only a portion of the ANP data message was environmentally related (for example, water temperature or insolation measurements).

Two-way relay is provided by the GOES transponders as shown in Figure E-1. The transponders are AGC'd (not hard-limit) and have a redundant backup. Buoys are interrogated by a continuous signal at ∿ 469 MHz, and reply on one of the 266 1.5 kHz wide channels at ∿ 402 MHz. The individual channels are time-shared by means of polling and scheduling. Satellites launched so far include SMS-1 and -2 and GOES-1 to -5. Satellites up through GOES-3 have electronically despun UHF antennas which impose a power-robbing spin modulation on the UHF signals. GOES-4 through -6 have mechanically despun antennas and no spin modulation. A full spare satellite is currently in orbit halfway between GOES-East and GOES-West. In addition, a high mortality rate among imagers has led to having additional satellites in which the DCS is available for backup.

The GOES satellites never appear lower than about 34° in elevation to virtually any point of interest in the contiguous 48 states (see Figure E-2). A hemispherical buoy antenna could therefore tolerate up to 34° peak libration due to rolling and pitching. (The multipath effects that could result from dipping the antenna pattern into the water could still be a problem, however.) To extend coverage to mid-Alaska (about 170°W, 65°N), the elevation drops to ∿ 12°, making the antenna problem more difficult. It may be cheaper overall to permit a different antenna type for the Alaska coverage. GOES-compatible communications hardware is available from at least eight different manufacturers.

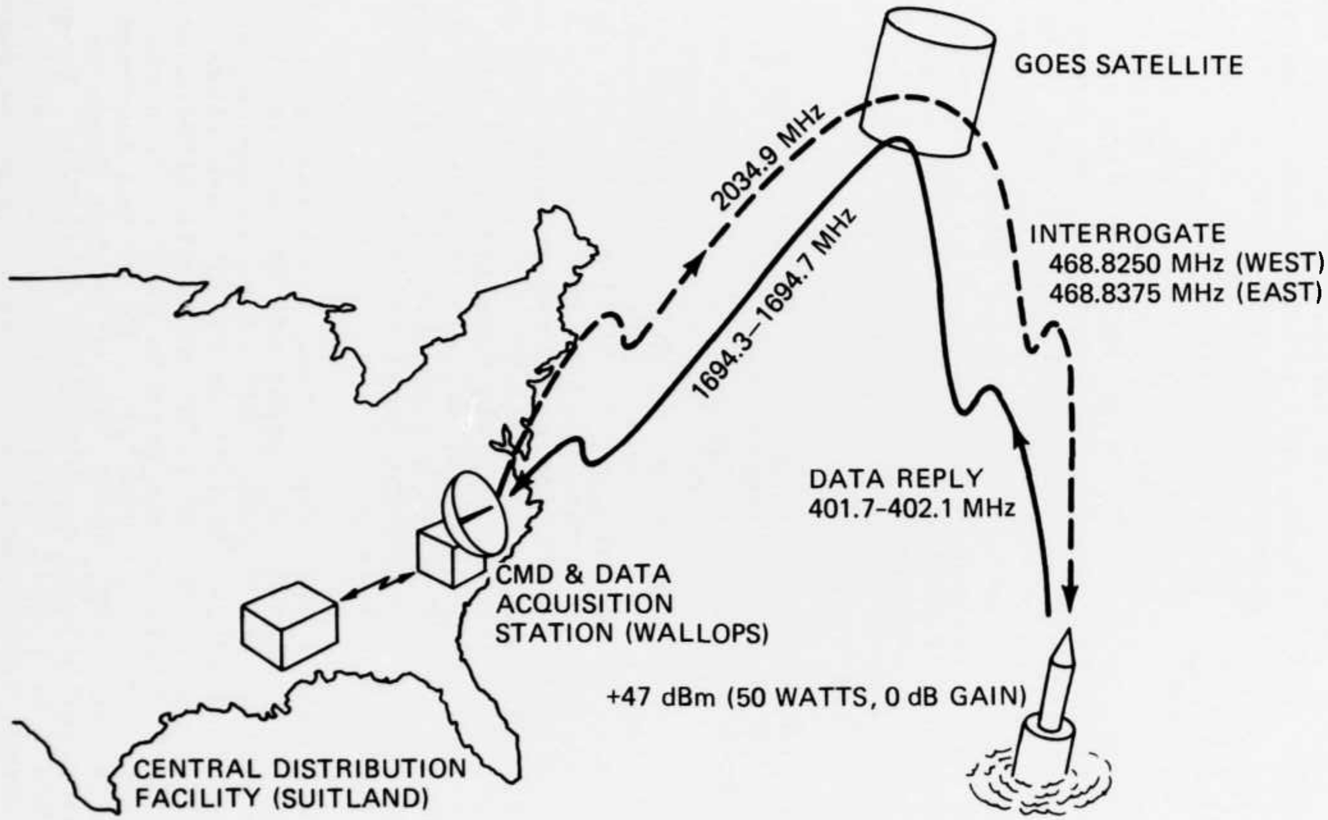

FIGURE E-1 GOES STATIONS AND FREQUENCY PLAN.

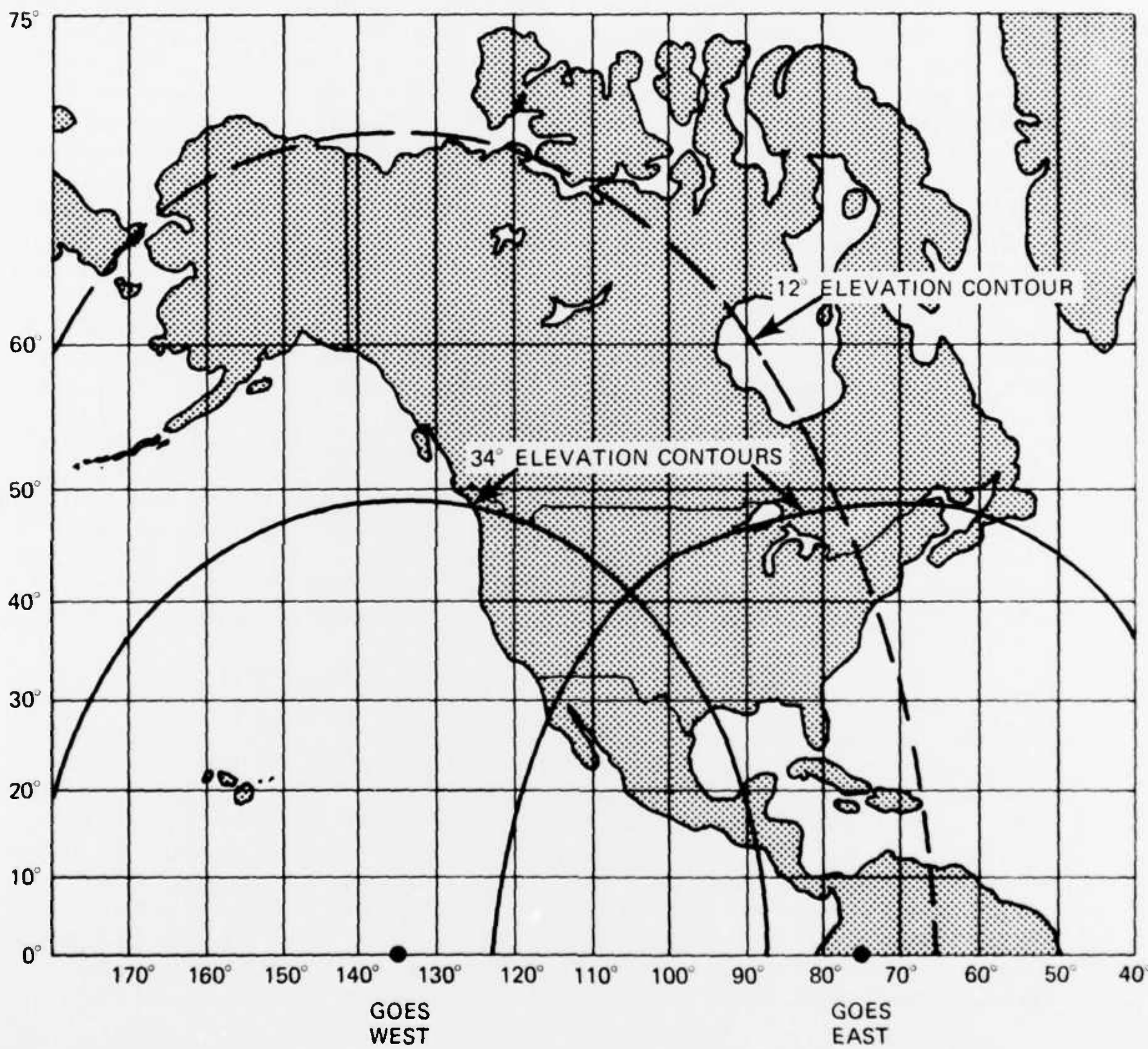

FIGURE E-2 GOES COVERAGE PATTERNS.

The GOES data user can choose from the following four modes of operation: interrogated, self timed, satellite timed, or random reporting. The interrogated user receives a continuous 100 bps digital stream on the 469 MHz downlink. The continuously transmitted interrogate signal is blocked into contiguous 50-bit words containing 15 bits of sync, 4 bits of timing data, and 31 address bits (see Figure E-3). A new address is presented every half second. When the user hears its address, it immediately responds on its assigned 402 MHz channel with reply data, also at 100 bps. The reply transmission consists of a 7.5 second preamble followed by 8-bit ASCII characters and terminated with triple end-of-transmission (EOT) characters. Arbitrary binary data can be sent using a pseudo-ASCII format with six data bits per 8-bit character. The signal received by the buoy is at least -139 dBm, and the buoy is expected to radiate +47 dBm (50 watts) nominal EIRP. The more recent GOES satellites have a more sensitive preamp, and there is some possibility of lowering the requirement in the future to perhaps +43 dBm (20 watts). The EIRP also must not exceed +50 dBm (100 watts) to prevent transponder takeover.

A block of 4096 addresses is reserved to enable the transmission of 12-bit commands to the buoy. In addition, the buoy can receive an NBS time code update every 30 seconds by accumulating 240 bits worth of the 4-bit timing words. This time mark can be made to 1 ms or better. The price the interrogate user pays for all this flexibility is the cost and complexity of a UHF receiver and a dual frequency antenna.

The self timed user needs no receiver. This user is assigned a periodic one minute time slot during which its transmission must occur (see Figure E-4). The long term stability of the user's internal clock must be such as to guarantee the message never drifts out of its assigned time slot. For short messages this amounts to 0.5 to 1.0 PPM per year, well within the capability of low-cost quartz oscillators. The buoy must be visited periodically (e.g., once per year) to re-center its timing. This user transmits with the same format as the interrogate user, but as a rule, different types of user are not assigned to the same reply channel. Ninety per-cent of the current GOES users are self timed.

If the self timed user did not have to contend with long term clock drift, large amounts of guard time on each side of the message would not be needed and channel efficiency would improve. A "satellite timed" user does this by receiving the NBS time code on the interrogate link and periodically correcting his clock. This requires a UHF receiver almost identical to that needed by the interrogate user, plus a resettable clock. In return, the user is free from having to periodically re-visit his buoy to adjust timing.

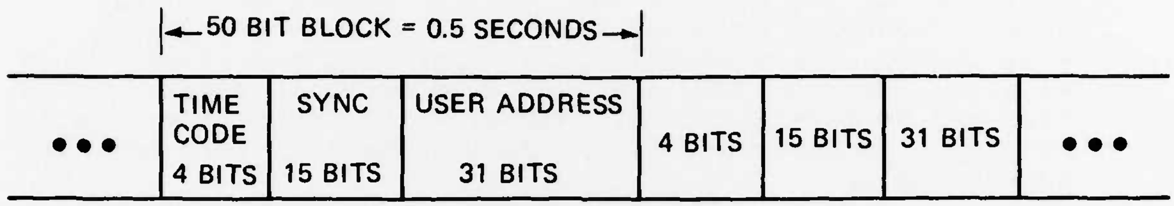

FIGURE E-3 INTERROGATE MESSAGE FORMAT.

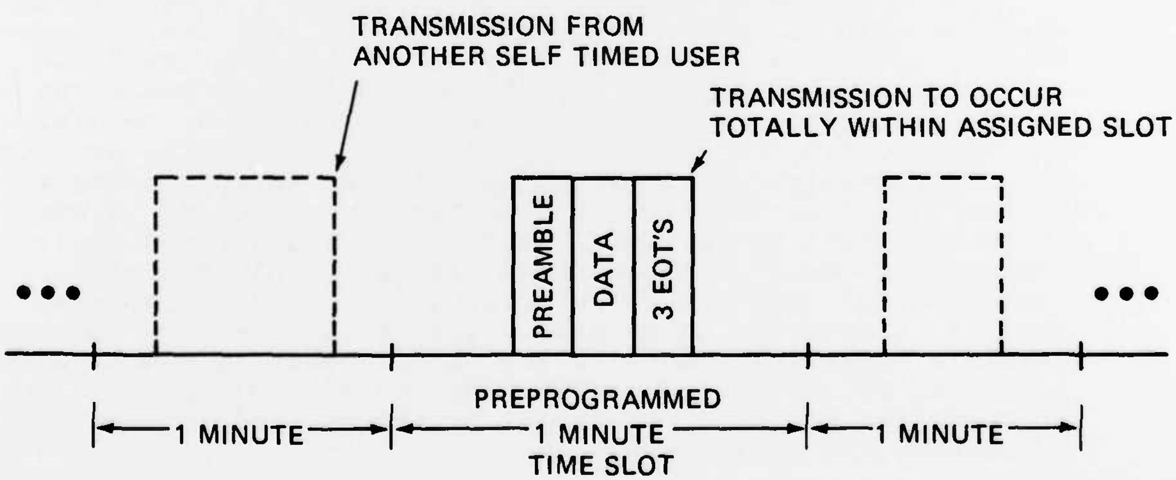

FIGURE E-4 SELF TIMED TRANSMISSION OPERATION.

The last type of user, "random reporting", makes short, very low duty cycle transmissions having random start times subject only to a fixed average time between transmissions. The number of users sharing a channel is adjusted so that the probability of any single transmission getting through without collision is 61%. Message reliability is achieved by repeating the message the required number of times. Random reporting presents some interesting exercises in statistics. The probability of successful reception can be made to approach 100%, provided some delay in message reception can be tolerated. Of course, random reporting does not require a receiver and has no particular long-term oscillator requirements.

Random reporting was introduced into GOES fairly recently. It quickly became clear that for communication efficiency the message must be as short as possible and in particular should not be burdened with the 7.5 second preamble. Equipment was therefore purchased for the CDA station that would allow acquisition with a 1.52 second preamble (includes buoy address). This equipment is currently in place only for the random reporting channels, but will probably be used for all modes in the future. The price paid for this shorter preamble is a somewhat reduced probability of acquisition under weak S/N conditions (but still probably > .999) and the possible need to impose a short term stability specification on the buoy transmitters (not expected to be a problem).

The GOES space segment is complemented by a well thought out user information dissemination system. All user contact is with the CDF in Suitland, Maryland. The user can issue interrogate schedules and receive buoy data messages using either full time dedicated lines (up to 9600 baud) or dial up lines to 1200 baud. Error conditions (such as an expected buoy transmission not received by the CDA station) along with system bulletins are also sent to the user. Coding is used to protect data integrity. The buoy interrogate and reply addresses themselves are encoded with a (31,21) BCH code. This powerful code can detect four and correct two errors. Reply data from the buoys are parity checked on each character. Landline communications with the CDF are sent in blocks with either an LRC or CRC-16 cyclic code and an ACK/NAK block retransmission protocol. Formats, protocols, and handshaking procedures are well documented.

Instead of receiving the buoy transmissions from the CDF, the user can elect to build and operate his own ground station to receive the S-band transmissions directly from the satellite. This would require a 10-30 foot diameter dish, low noise amplifiers, downconverters, demodulators, and bit synchronizers in addition to the already required data handling equipment. Currently, about a dozen GOES users operate their own stations. Considering the large number of buoys involved in the ANP

system, this may be an attractive option for the Coast Guard.

The GOES system also includes a test mode to enable field installers to verify operation of buoys immediately after installation or repair. This is done by initiating scheduled test transmissions from the buoy in the field. When the CDA receives the transmission correctly, it signals the field installer by sending the buoy's "secondary address" on the interrogate link. Receipt of this signal by the field installer (using either the buoy receiver or a separate test receiver) confirms the operation of the full round-trip data path and gives high confidence in the buoy installation.

Before leaving the GOES system description, two minor problems should be mentioned: system outages and interference. Because the GOES satellites are geosynchronous, they experience solar eclipses during 46-day intervals centered on the vernal and autumnal equinoxes. The eclipses occur during local midnight for the satellites' meridian and vary in duration from 10 minutes up to 72 minutes. During eclipse, the transponder power is cut back by 1-3 dB or may be shut off entirely, depending on satellite health. Service interruptions may also occur due to planned periodic maintenance at the CDA station. This source of outage is expected to become less important as redundant station facilities are installed. Neither of these outage situations present insolvable problems for ANP system.

Potentially more troublesome is the fact that the GOES interrogation frequencies (468.8250 MHz West, 468.8375 MHz East) share an allocation with the "land-mobile" service. In fact, GOES is the secondary user, and so no relief can be expected from the FCC in resolving interference problems. Interference is more likely to occur in urban areas and when receiving the western satellite. This situation will have to be looked at carefully if the GOES option is persued.

GOES APPLICATION TO ANP

To see how the various GOES data collection modes apply to the ANP, several assumptions are made. First, it is assumed that the shorter preamble (1.52 sec including address) is available to all types of user, not just random reporting. The transmission length is taken as 4.0 seconds, as follows:

Preamble (including buoy address)	1.52 sec
28 pseudo-ASCII characters	2.24
3 EOT's	.24
	4.00 sec total

The 28 message characters contain the arbitrary buoy data with a 6/8 packing efficiency, or 168 bits net data. The message is assumed to be sent once per day from each of about

20,000 buoys. Message delay is defined as the time between when an event occurs on the buoy and it becomes known at a shore station.

Table 3 shows a comparison of the four GOES modes discussed previously along with a hybrid mode that will be proposed below. The interrogate mode would serially poll all buoys in a day. To allow some protection against timing errors and path length differences, a minimum of 0.5 second guard time is added after each 4.0 second transmission. There are then 19,200 possible buoys per channel per day, tightly packed. To provide some additional margin, it may be desirable to utilize two reply channels with looser timing. To poll these buoys requires 5.6-11% of the total time on the interrogate channel, depending on how they split among GOES-East and -West. So while the interrogate mode provides the most flexible access to the buoys, it does require a GOES receiver and imposes a significant burden on the interrogate link.

For self timed, each buoy transmits within its preassigned one minute time slot. Since there are only 1440 minutes/day, 14 channels are required to accommodate 20,000 buoys. If the 4.0 second transmission is initially centered in its slot, it can drift no more than ± 28 seconds. This imposes a long term oscillator stability requirement of 9×10^{-7} per year, assuming once per year readjustment is permissible. To maintain < 28 seconds drift over the desired five years in the marine environment would begin to impact the oscillator cost, power, and reliability.

The satellite timed mode would pack 19,200 transmissions per day on one (or two) channels, much like the interrogate mode. The transmissions would be initiated by NBS time reception, rather than by interrogation. Therefore, while a receiver is still needed to receive time, no burden is imposed on the interrogate channel. Oscillator stability requirements are minimal and depend mainly on how frequently the receiver is turned on for a time update. Circuitry for maintaining, resetting, and recognizing time-of-day is required, but this is about equivalent to the address decoding and recognition circuitry required in the interrogate mode and not needed here. The satellite timed mode places minimal demands on the GOES links, but instantaneous access to any desired buoy is not possible. It should also be pointed out that the "satellite" timed mode could also receive its time information from sources other than GOES. It is unfortunate that the Loran-C signal does not contain time-of-day information.

In the three modes discussed so far, the maximum message delay is one day, and the average delay is half that. With random reporting, the message delay becomes a statistical parameter. Using five repeats of the message ensures that the

message will be received with probability 0.99, although it could take up to five days. There is a 0.61 probability of reception on the first try when the channels are optimally loaded. Using the recommended GOES "Method 3" of repeating messages, once a day at random the following transmission is sent:

preamble (including buoy address)	1.52 sec
latest (n^{th}) data message	2.24
repeat of $(n-1)^{th}$ message	2.24
repeat of $(n-2)^{th}$ message	2.24
repeat of $(n-3)^{th}$ message	2.24
repeat of $(n-4)^{th}$ message	2.24
3 EOT's	.24
	12.96 sec total

Thus in the course of five days each message gets repeated five times, and the probability of success is:

in 1 day	P = 0.607
in 2 days	P = 0.845
in 3 days	P = 0.939
in 4 days	P = 0.976
in 5 days	P = 0.991

The optimal performance is achieved when the channels are loaded to 25% capacity, or 1667 buoys per channel per day for the ANP transmission length. So for 20,000 buoys the full time use of 12 channels is needed.

PROPOSED GOES OPERATING MODE

Reviewing the four standard GOES modes, as applied to the large network of buoys, we see that both self timed and random reporting impose heavy loads on the GOES reply channels, while the interrogate mode likewise loads the interrogate channel. Only the satellite timed mode is conservative of both type of channel, but at the cost of requiring a GOES time receiver. If we assume that some kind of receiver is required anyway to satisfy the rippling light requirement, then it may as well be a GOES receiver. This receiver can then provide NBS time for the rippling light and satellite timed communications, and also a limited amount of interrogation of specific buoys. The proposed hybrid scheme is shown in Figure E-5.

In the proposed hybrid, the day is divided into 19,200 4.5-second time slots, with a buoy assigned to transmit its 4.0-second transmission centered in its slot. In addition, every six hours the GOES receiver is turned on to re-sync the buoy clock and to listen for the addresses of any buoys

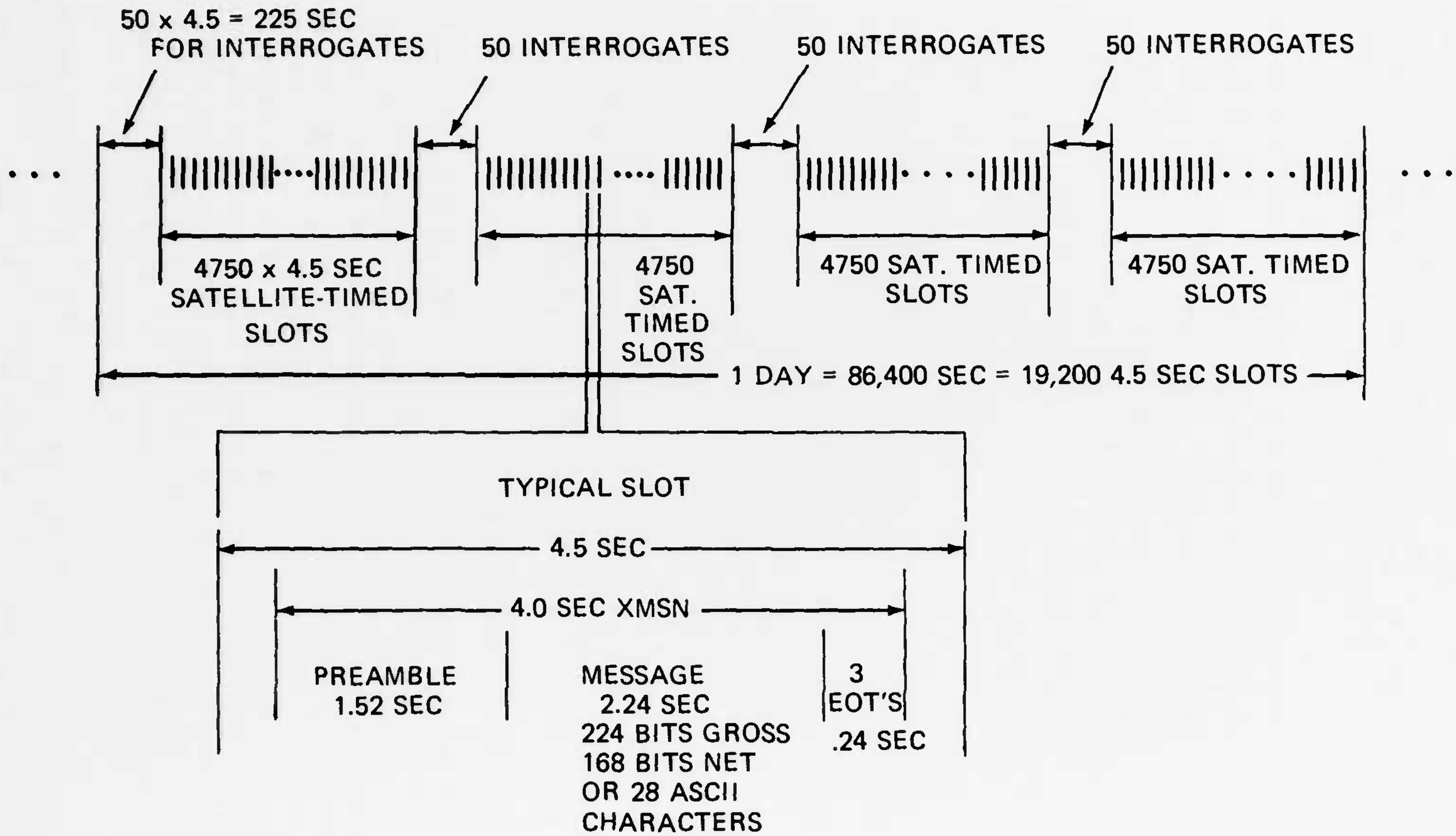

FIGURE E-5 PROPOSED HYBRID GOES FORMAT.

that are to be specifically interrogated. No other satellite timed transmissions are programmed during the four 3.75-minute interrogate slots that occur each day. Since the buoy clock is re-synchronized four times per day, the oscillator drift requirement is reduced to a trivial 1×10^{-5} over six hours, which reduces oscillator cost and power. The maximum waiting time for any specific buoy is reduced to six hours, with up to 50 buoys being interrogated every six hours. Normally the only buoys that would be directly interrogated would be those reported out of order, those that didn't report in on their scheduled time, or those with suspect data. The ratio of 50 interrogates for every 4750 satellite timed slots is only illustrative. The actual split would be optimized based on Coast Guard data. Technically, the GOES system requires that interrogated replies be made on a channel (frequency) different from the satellite timed replies. Informal discussions with NESS indicate that for a user as large as the ANP system, a whole channel could be dedicated to the Coast Guard and both types be made on the same frequency. This simplifies the transmitter and lowers its cost. It might also be desirable to not have each buoy report at exactly the same time each day, but rather to "roll" the buoys through various time slots. This would provide some protection against interference and would be easy to implement.

DAT

ILM